Membranes are thin, flexible surface structures carrying loads through tension stress; net structures are different in that they have surfaces made from cable net meshes; both adapt to loading and are sensitive to aerodynamic effects of wind (*fluttering*).

Stabilizing is usually necessary and be from rigid supporting framework or prestressing (pre-tensioning).

Transverse loads are distributed by tensile forces in the surface of the structure (in-plane) and tangential shearing stresses (in-plane) are developed and manifests as a twist; surfaces cannot go into tension and still carry load!

Pneumatic membrane structures obtain stability by internal pressurization; most use air; classifications of air-supported (single membrane with internal pressure differential) and air-inflated (inflated building elements having pressurized air).

Air supported uses small pressures with relatively small loads to keep membrane in tension and avoid compression stress; has to have air locks and edge anchoring to the ground and preventing leakage; usually greater spans than air-inflated.

Air inflated uses shapes to form the building enclosure; pressure forms shape rather than to directly balance the external load.

Snow load can accumulate on an air-supported structure, usually only near the crown (usually melts from heat loss); large concentrated loads must be avoided due to high stresses; wind loads result in suction and tension with respect to the aspect angle.

In-plane membrane forces depend on the dimensions, shape and pressure; spherical \( T = pR/2 \); two curves \( p = T_1R_1 + T_2R_2 \); cylindrical surface \( T = pR \); force per unit length (line stress) \( f = T/tL \).

Internal pressure has to be large enough so compression/folding doesn’t occur (and tensile stress isn’t exceeded in the material).

Air-supported structure must be anchored and the anchor will be in compression from the upward and inward forces (usual); wind can change the direction of the forces.

When air-supported structures are large span and require a cable-net type of membrane, the junction of the cables and containment ring result in high local stresses.

Choosing the profile of an air-supported structures is critical; high profiles (small radius) require less pressure than low profiles (high radius); high profiles can enclose more volume with increased demand on mechanical systems; low profiles are less sensitive to wind pressure and can result in suction (no pushing) only.

Air-inflated structures are prestressed in tension to make them rigid and when loaded the stresses are combined and must not go into compression (which isn’t possible).

Design concern of pneumatic structures is punctures; with air-inflated and low pressures, you get a slow leak.

Design concern of durability of membrane materials with UV light and exposure.
Net and tent structures are prestressed in tension and require cables or support elements; sharper surface curvatures result in stiffer membranes or nets; flat areas must be avoided because the amount of prestressing is enormous (large); high points are usually separated by low points.

High points are obtained by large compression masts with low points usually ground connections; ground will see high horizontal and vertical forces; more supports, the less the force per support.

Free edges of nets are often stiffened with edge cables under high tension to develop more uniform tension field in the net.

High stresses at high points are diffused with opening the point and providing a cable ring connected to the mast.

Form finding is complex and nets are often made up of multiple smaller pieces; physical modeling is helpful; computer modeling helps define stresses and shapes with the effect of weight.

Net materials have different strength and stretch properties in the warp and weft (thread) directions and can creep; materials include PVC-coated polyester, Teflon-coated glass fiber or silicone-coated glass fiber; cable materials are usually high-strength steel (can corrode); ends of cables are critical—clamps or fittings.

Three-dimensional surface shapes are categorized as single-curved, double-curved; double-curved can be classified as synclastic (curves turning the same way all sides) or anticlastic (not) or saddle-shaped (hyperbolic paraboloid); can be generated by rotation of a curve about an axis, translational surfaces, ruled surfaces, and combinations.

Computational methods help define complex surfaces, so design focuses on determining efficient shapes and constructing them.

Curved surfaces only effective in being stiff by enabling efficient membrane forces to develop (just because it curves doesn’t mean it is necessarily stiff or better).

Shell or membrane action is when primary internal forces developed under load lie within the plane of the surface and are in tension or compression (membrane forces and stresses); bending stresses are minimal (book says not normally present) which allows the shell to be thin; (developing bending stresses, which are maximum at only a few places in the cross section, is considered inefficient, whereas tension and compression—stresses across the full cross section—are).

Structures with membrane stresses (shells) are suited to carrying distributed loads and are usually used for roofs; can’t carry concentrated loads; see tension, compression and shear stresses in plane; can span great distances with span to thickness ratios of 400 or 500.

Reinforced concrete shells are recent, while masonry domes are not considered shells (having no in-plane stresses and bending).

Terminating a shell surface is “problematic.”

Shell shapes made out of short bars behave like membranes with axial forces in the bars; geodesic dome uses bars of equal lengths (Buckminster Fuller); lamella is a ribbed barrel shape with large spans—typically in wood, but has been done in concrete and steel.

Ferrocement (concrete with small aggregate and large amounts of reinforcement) is used in Nervi’s dome at Il Palazzetto dello Sporto; tension ring at the base must resist outward forces from Y shaped buttresses so they constructed a postensioned reinforced-concrete ring.

Behavior of shells is comparable to membranes with primary internal forces acting in perpendicular directions along with tangential shearing stress; also comparable to two-way plate behavior.
Meridional forces are analogous to arch forces under full loading; hoop forces are in the circumferential direction and perpendicular and restrain the out-of-plane movement of the meridional strips in the shell, but still no bending; shells can carry variation in loading due to the development of in-plane stresses only as long as the variation is gradual; sharp discontinuities will cause bending

Stresses in the meridional direction are always compressive under distributed load, while hoop stresses are in compression for about the top third and go into tension on the lower section; fairly small stresses; holes should be avoided if efficiency is desired, but if they are used, edges must be reinforced

With a uniform gravity load from \( w \), \( W = N\phi \sin(2\pi a) \) for the meridional force per length and \( a = R\sin\phi \), with stress of \( f_\theta = N/\ell \). \( N_\theta = Rw/(1+\cos\phi) \)

With a uniform gravity load from \( w \), the hoop force per length is \( N_\theta = Rw(-1/(1+\cos\phi)+\cos\phi) \) and the stress is \( f_\theta = N/\ell \)

If the angle of cutoff, or aspect angle is less than \( 51^{\circ} 49' \), the hoop forces will all be compressive

Concentrated forces should be avoided because the meridional stress becomes infinitely large

The design of the supports for a shell is major; a tension ring could be used to resist the tensile stresses of a spherical dome base where \( T = N_\phi \cos\phi \); a compression ring is needed if a hole is at the upper portion which is in compression in the hoop direction; tension rings can be anchored to the foundation, or on columns, but there will be bending moments at the supports which rapidly decrease away from the base; a roller support is ideal but extremely difficult to construct

Posttensioning can be used to minimize deformations through pre-compression at the support and also in the hoop direction

Local buckling (snap through) must be prevented and can occur because of large slenderness ratios and under low stress in compression

Wind load (and other later loads) can cause the far surface to see compression (and buckling) when tension was expected under gravity loads

Cylindrical shells that are long (length 3 x transverse span or more) are considered barrel shells and the stresses are beam-like without arching action through the curved section; the edges that aren’t stiffened tend to deflect inward under gravity loading; transverse stiffeners increase the load-carrying capacity

In hyperbolic paraboloid shells, archlike action will exist with convex curvature and cable-like action with concave curvature; flat sections may have bending dominate; under uniform loading at the top of any arch or cable strip \( C_x = T_x = wL_x^2/8d \) or \( wL_x^2/16d \) with \( w \) as the normal distributed load; \( C = -wab/2h \) and \( T = wab/2h \); membrane force is more or less constant throughout the entire surface; edge shear exists and are approximately \( F = wab/2h \) with a large total to the restraint points of \( F_{total} = wa^2b/2h \); edge beams may be needed or tie rods

Free-form shapes can be generated computationally; if bending arises, the shape is not behaving as if a membrane

Grid-shells have interconnected networks of curved or linear members to produce a surface with strength and rigidity to resist in-plane forces and some bending; common to see surface cables for stabilization
Membrane fabric materials with threads include cotton (natural), polyamide 6.6 (nylon), polyester, fibreglass, aramid fiber (kevlon); fibers have covering to protect from weathering and pollutants, usually PVC, teflon or silicone.

Mechanical behavior of fabrics – non-linear, anisotropic, non-elastic.

Membrane design requires a balance between pretension in the membrane and the boundary conditions (supports and free edges).

Membrane failure modes – failure of the bi-axial loaded membrane within the assumed lifetime of the structure, failure of a seam or connection of membrane to primary structure, tear failure during installation or because of vandalism.