ARCH 631. Topic 13 Reading Notes

- 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 $T = p_r R/2$; two curves $p_r = T_1/R_1 + T_2/R_2$; cylindrical surface $T = p_r R$; 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 an 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 discontinuties 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, $W = N_\phi \sin\phi(2\pi a)$ for the meridional force per length and $a = R\sin\phi$; with stress of $f_\phi = N_\phi/t$. $N_\phi = Rw/(1+\cos\phi)$
- 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 $f_\theta = N_\theta/t$
- If the angle of cutoff, or aspect angle is less than 51° 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 $T = N_\phi \cos\phi a$; 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 cablelike action with concave curvature; flat sections may have bending dominate; under uniform loading at the top of any arch or cable strip $C_x = T_x = w_s L_x^2/8d_x$ or $wL_x^2/16d_x$ 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