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Structures Using Uncurved or Minimally Curved Tensioned Fabric Membranes

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Introduction

Most tensioned fabric structures employ membranes that have support geometry resulting in anti-clastic curvature. A lesser number of structures have synclastic forms maintained by air pressure. Fabric membranes with little or no curvature must deflect substantially to resist out of plane loads, and their inefficient load resistance may result in high membrane stresses and heavy loads on the supporting cables and rigid elements. Large deflections may also result in conditions where membrane slope reaches zero under rain or snow loading, with ponding resulting. Uncurved or minimally curved surfaces are therefore generally avoided in design.

Architectural, economic, or other reasons create many instances in which uncurved or minimally curved fabric membrane surfaces are desirable. Fabric roofs employing flat membranes can be economical, beautiful, and practical in certain conditions and with appropriate attention to the special design problems that are associated with them. The paper presents case studies of several recently built structures that employ uncurved or minimally curved fabric membranes. It explores the rationale behind the selection of flat forms, and considers how the special risks or costs associated with inefficient load resistance, high deflection, and the threat of ponding were addressed. The structures studied are recently constructed designs engineered by the author.

Membrane Structure Load Carrying Behavior

Membranes formed of woven fabric, film, or other materials have minimal thickness and therefore negligible load resistance through compression and bending mechanisms. Roofs or enclosures employing structural membranes therefore rely on the tensile strength of the membrane, in combination with mast, strut, or arched compression elements and beam or truss bending elements.

Most tensioned fabric structures employ membranes that have support geometry resulting in anti-clastic membrane curvature, wherein outward loads are resisted by an increase in stress in the hogging fibers about one axis of the membrane ("A" in Figure 1) and inward forces are resisted by an increase in stress in the sagging fibers about the other axis ("B" in Figure 1). Anticlastic forms are the result of support conditions that produce saddle or conical forms. A lesser number of structures have synclastic curvature, akin to that of a bubble, in which outward forces are resisted by hogging fibers in both

axes of the membrane and inward forces are resisted by air inflation or air support. In both anticlastic and synclastic forms, load resistance is dependent on shapes that provide substantial curvature about opposing axes of the membrane. Considered in the simplified form of a planar curved tension element (a cable) with its ends at the same elevation, the horizontal force in the cable (a good approximation of the actual force in a minimally curved cable) is defined by the formula

$$F = wl^2/8h \tag{1}$$

Where “w” is the load per unit length “l”,
and “h” is the sag in the tension element

There is an inverse linear relationship between h & F, such that, as the sag in the cable approaches zero, the cable force approaches infinity. To solve the force equation, a sag must be assumed and the resulting force calculated. This force is checked against the force resulting from the cable elongation that is associated with the assumed sag. The assumed sag is then adjusted iteratively, until the equation converges. A decrease in stiffness of the cable will result in increased sag, and a consequent reduction in cable force. Extrapolating this principle to three dimensions, we see that the load resistance of uncurved membranes is improved by low stiffness and consequent large deflections.

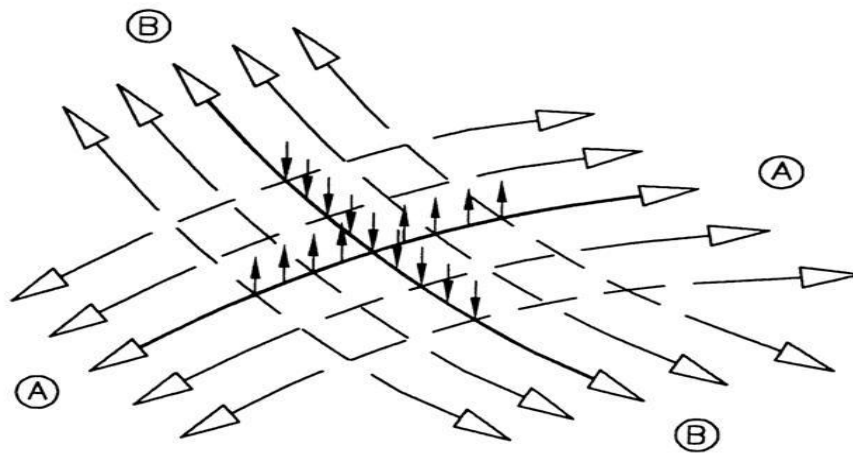


FIGURE 1

The hogging fibers of an anticlastic membrane (“A”) resist upward loads, while the sagging fibers (“B”) resist downward loads

Strategies for Successful Uncurved Membrane Structures

Membrane structures in which all lines or points of support lie within the same plane will have zero curvature under prestress conditions. In some structures, initial membrane curvature is so slight that areas of the membrane will “pop through” or change sign of curvature under load. The behavior of such structures is similar to that of uncurved membranes, in that resistance to external loads is dependent on substantial deflection under load rather than on initial curvature. For purposes of this report, membranes that

are uncurved and those subject to change in sign of curvature under anticipated external loads will both be termed “flat membranes”.

Two sets of risk are inherent to structures that employ flat membranes. The first relates to their inefficient load carrying mechanism. Because they have little or no initial curvature, membrane sag in the loaded condition tends to remain smaller than in membranes with substantial initial anticlastic or synclastic curvature. Referencing (1), membrane stress therefore tends to be high relative to span and loading. These higher membrane stresses increase the required membrane tensile strength. They also cause higher loads on the cables or rigid members that support the membrane, with the result that these supporting elements have increased physical and visual mass, and generally decreased economy and beauty. These higher loads can often be traced all the way to grade, with the final consequence of larger footings to support the increased loading. The inefficient load resistance of flat membranes may result in designs that are both aesthetically coarse and uneconomical, particularly in large structures.

The second set of risks associated with flat membranes relates to their inherent large deflections under load. Large deflections are associated with large changes in membrane slope, such that membranes with moderate initial slope may become flat or even reverse their slope under load, thereby preventing snow or water from reaching the membrane edge. The danger of ponding must therefore be carefully evaluated in membranes with areas of moderate slope under prestress. Large deflections also present serviceability risks of wind induced movements that cause noise or unease in building occupants, or that increase wear on the membrane or cable fittings.

Avoidance of the risks associated with inefficient load resistance calls for designs with low membrane modulus of elasticity and large resultant sag under load. The properties of the elements supporting the membrane can also be manipulated to allow greater inward displacement of the membrane edge under load and larger resulting sag in the membrane, as follows:

- Where the membrane is bounded by perimeter catenary cables, low sag in the cables in the prestress condition dictates that the cables pick up force rapidly under external load (ref. Equation 1), and therefore have greater elongation and increase in sag than cables with large initial sag.
- Where the membrane is fastened to beam elements along its perimeter, low bending stiffness in these elements results in greater deflection and displacement of the membrane edge.
- Unguyed supporting masts generally experience significant bending deflection under load, such that the membrane attachment points deflect inward to increase membrane sag more than with guyed masts.

The strategies for addressing the risks of inefficient load resistance are unfortunately those that increase the risks associated with large deflections. The most successful designs seek both to moderate membrane stiffness and to configure the membrane so as to maintain high initial slopes, especially when environmental conditions create situations with high ponding risk. In structures where geometric constraints result in marginal initial membrane slope, the designer may choose high membrane prestress or reduce membrane span through the use of ridge cables or rigid internal support members.

Burnside Courtyard Canopy

Archaeo Architects' design for this home is broad and close to the earth, and incorporates three low fabric shade canopies to provide relief from harsh New Mexico sunlight. In keeping with this aesthetic, the architects envisioned its 13m square center court shaded by a horizontal fabric canopy with an 8.5m diameter center oculus (Figures 2 and 3).

Fabric spans on the canopy are small, and the inefficiency associated with the lack of curvature in the membrane therefore imposed little penalty on the economy of the construction. As conceived, however, the slope of the canopy was limited to the small sag at the oculus created by the dead load of the canopy and its catenary edge cable. The form was subject to large wind induced deflections, and had no ability to drain snow. (Snow load, when snow drift below the surrounding parapets is considered, is a maximum of 1.6 kPa at the mountain top site.).

Manipulation of the form was required in order to increase the slope to a level that would both moderate wind induced deflections and assure sufficient slope for drainage of snow towards the oculus. The correction of form was achieved through the use of steel wide flange beams that cantilever from the walls at the center of each of the four sides, and terminate with vertical compression struts that push the oculus catenary cable



FIGURE 2
Burnside Courtyard Canopy

downward at its quarter points. The struts are formed by stainless steel all thread rods, and threading the rods downward provides a means both of inducing the required canopy slope and pretensioning the catenary cable and membrane. The added elements maintain the visual elegance of the original concept.

Archaeo conceived the canopy with gaps of 80mm between the membrane and the surrounding stone clad walls. The gaps allows light to pass between the wall and membrane, and distinguish the two as discrete design elements. A small steel tube inserted in the fabric cuff maintains the straight fabric edge, and small stainless steel turnbuckles secure the membrane to the wall and provide a secondary tensioning and adjusting mechanism (Figure 4).



FIGURE 3
Burnside Courtyard Close Up



FIGURE 4
Burnside Wall Anchorage

Springboro Amphitheater

The cover for the amphitheater in Springboro, Ohio provides shading for the stage and seating areas, and is the dramatic feature of the community park. The design concept of architect Lorenz & Williams included two overlapping fabric canopies. The upper membrane is bordered by catenary cables spanning between three support masts. Because the membrane is three sided, its shape is inherently uncurved. The lower membrane has four sides, also bordered by catenary cables, and the elevations of its four corners are configured to provide a small amount of anticlastic curvature. The corners of both membranes are supported by steel pipe masts guyed back to grade (Figure 5).

The unsupported span of the fabric is as much as 20m, and the maximum catenary cable span is about 36m. These spans are large for flat membranes, and were of particular concern for a structure supporting snow loads (1.0 kPa at ground). Not unexpectedly, analysis indicated large catenary cable forces, with resulting diameters ranging from 22mm to 38mm. The magnitude of their load is evident in the relatively massive membrane plates and clevis attachments (Figure 6). The catenary cables impose

large forces in turn on the 305mm diameter masts, which are each restrained by double tieback cables of 19mm to 51mm. Foundations are subject to large uplift forces, which are resisted by helical screw anchors.

The membranes undergo large deflections under load – a maximum of greater than 1.0m downward under snow loading on both upper and lower canopies. The slope of the upper membrane is sufficient to prevent snow build up on its surface. The lower membrane, however, has relatively small slopes, with anticlastic curvature that is insufficient to prevent it from reversing curvature about one axis under load. In addition, the orientation of the upper membrane slope causes water and snow to drain towards the catenary edge which lies above the lower membrane, allowing this load to build up on the lower canopy in extreme weather conditions.

The Huntington Design engineers employed special measures to combat the risk of snow and water ponding, including high membrane prestress. In addition, an internal ridge cable was added to shorten the effective span of the fabric under potential downward (snow) load. The ridge cable also provides visual accentuation of the shape of the membrane. Nonetheless, ponding of freezing snow occurred when the upper membrane dropped its snow load onto the lower membrane in sufficient volume to create an area in this canopy that was at lower elevation than the catenary and ridge cables bordering it.

To prevent recurrence of the ponding, 22mm diameter drain holes were installed at 5 locations in the area of the membrane most vulnerable to ponding. The drain holes were reinforced with doubled fabric reinforcement, and were placed along fabric seam lines in order to limit their visibility. The proper functioning of the drain holes is a function of the ability of water to find a clear path to the drain, and heat trace cables were installed along the two seam lines containing drain holes to melt accumulated snow locally and assure water flow.



FIGURE 5
Springboro Amphitheater Canopies



FIGURE 6
Springboro Mast Top Connection

Reliable resistance to ponding is dependent on periodic inspection to assure both the reliability of electrical power to feed the heat trace cable and that the membrane

remains clear of debris that might clog the drains. The design provides several lessons regarding appropriate shaping of fabric membranes to achieve reliable load resistance, as follows:

- Flat membranes should be avoided in long span applications where significant snow load may occur.
- Analysis should demonstrate that there is minimal possibility for any area of the fabric to pass through zero slope before water reaches the edge of the membrane and ponding may occur. Membrane support point geometry should be adjusted where required to provide sufficient slope.
- Careful attention should be paid to the risk of stacking one roof or membrane above another in such a way that the upper canopy deposits substantial water or snow onto a lower canopy. Slopes may be reversed or gutters added to prevent this occurrence.

Springs Preserve Photovoltaic Structures

The growing market for photovoltaic arrays has brought with it the exploration of increasingly sophisticated means of supporting and configuring photovoltaic panels, as well as greater diversity in the siting of photovoltaic arrays. Arrays are most often located at grade or on the roofs of buildings. Ground mounted arrays consume substantial acreage, however, and reduce the effective environmental sustainability of such installations, while the unsuitability of many building roofs to photovoltaic array installation limits roof top installation as a means for satisfying the growing market for photovoltaic power.

Parking covers are one of several emerging venues for array installation. By using framing to support solar panels overhead of outside parking areas, the land is given dual use, and no additional site area is consumed by the solar array. In addition, the arrays provide shading to increase the comfort of those using the parking.

Novel recent projects have demonstrated the value of architectural fabric membranes in improving the power generation efficiency, beauty, and serviceability of photovoltaic arrays used in parking cover installations. In these applications, fabric is used as an interlayer between parked vehicles and an overhead photovoltaic array. The panels used in these applications are recently available “bifacial” panels, which are photovoltaically active on both top and bottom sides. The fabric provides an effective surface for reflecting sunlight onto the undersides of the panels, while at the same time improving shading of the parking and relieving some of the visual clutter of the array for those using the parking.

The increase in power production associated with bifacial panels is a function of albedo, which is a measure of the portion of light striking the surface beneath the panel that is reflected back upward. Typical albedos range from 0.10 for foliage or asphalt, to 0.30 for concrete, up to approximately 0.80 for snow. The gain in photovoltaic output associated with the incorporation of fabric membranes is primarily a function of the high albedo of fabric relative to that of the typical asphalt of concrete parking lot paving. If white fabric is used to maximize reflectivity, albedo generally varies from about 0.65 for mesh material to 0.75 for solid membranes.

Las Vegas Springs Preserve is a visitor center with displays and events focused on sustainability in the desert environment. A total of six photovoltaic arrays are

constructed over visitor parking areas to create dual land use (Figure 7). In two of the arrays, fabric membranes are installed above the parking but below the photovoltaic panels. The need for uniform reflectivity necessitated that the fabric be nearly horizontal throughout its surface, as did the need to place the fabric well overhead of the parking and below the array, while at the same time avoiding the added expense of raising the elevation of the array. Photovoltaic contractor Sunpower initially conceived the fabric as flat and uncurved membranes, as a result, and proposed a white Ferrari 492 mesh as a means of allowing water drainage on the flat panels.



FIGURE 7
Springs Preserve Photovoltaic Parking Covers

As discussed above, uncurved membranes induce higher loads on the supporting structure. The flat membranes were also subject to excessive deflection. Three rows of membrane panels are provided across the width of the structure (Figure 8). As a means of bringing modest curvature into them, the rectangular panels were designed with six attachment points to the supporting steel. The four corner points connect at the same workpoint elevation on the top surface of the primary steel girders. Intermediate attachment points along two opposing sides are secured at lower elevation. The figure

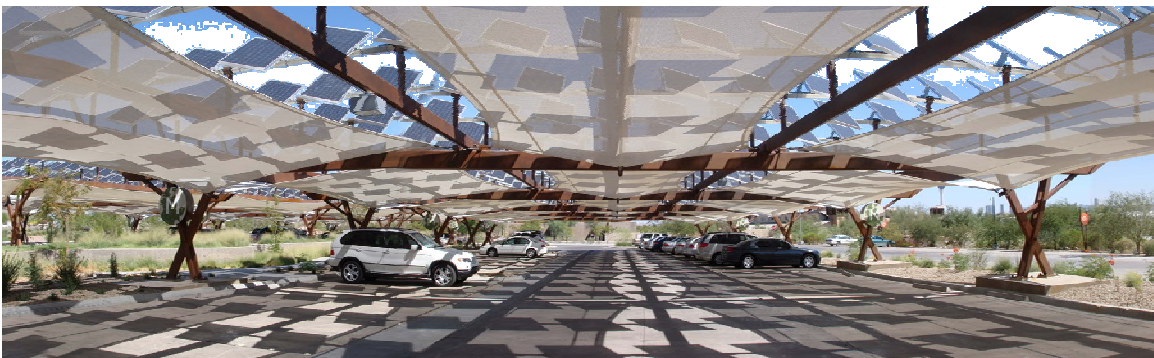


FIGURE 8
Fabric membranes improve shading and appearance beneath the photovoltaic arrays

shows how the intermediate anchorage points of the center panels are secured to the underside of the main girders and the intermediate anchorages of the side panels are secured to the sides of the steel supporting columns.

Analysis indicated that the side panels would deflect sufficiently at their midpoint to impact the large overhead transverse girders under wind uplift forces. Valley cables were therefore added between the intermediate anchorages. The cables pull the fabric into a lower profile along the valley line and increase its stiffness to prevent impact and provide a more visually dynamic curvature.

The final design maintains the mesh fabric, resulting in a lower albedo than with a solid material, but still providing power output about 18% greater than single sided panels, based on the results of testing done by Sunpower on prototype panels. The mesh provides a “soft” barrier to vision and light, relieving the visual clutter of the arrays overhead and providing gentle shading of vehicles and visitors below.

For the fabric to provide economic value to the project, it was important that its installed cost not exceed the value of its contribution to energy generation. Simplicity in fabrication and erection were therefore critical elements of the design strategy. Structural bay widths are a uniform 11m, to provide duplication in patterning and fabrication.

Fabric panels are bordered by galvanized steel catenary cables, and the catenaries are secured to membrane plates at the corners of each fabric panel that are in turn anchored to the supporting steel (Figure 9). Simplicity, repetition, adjustability, and visual elegance were the goals of the connection designs. All membrane plates and stainless steel jaw fittings are identical, and the stainless steel threaded rods anchored to the supporting steel provide both tensioning mechanisms and adjustability for fit up. The intermediate panel connection points employ custom fabricated stainless steel fittings, in which the catenary cable rides across the head of the valley cable spade end fitting (Figure 10).

The fabric panels extend past the edges of the array to provide their reflective benefit throughout, but the gaps between fabric panels created by the catenaries reduce the effective albedo beneath a small portion of the panels. This was considered an acceptable loss in view of the improved economy, speed of erection, and visual richness provided by the curved fabric openings. The enlivening visual character of the fabric catenary edges is particularly evident at the edges of the structure (Figure 11), where the curvature of the membrane contrasts with the hard lines of the steel framing.

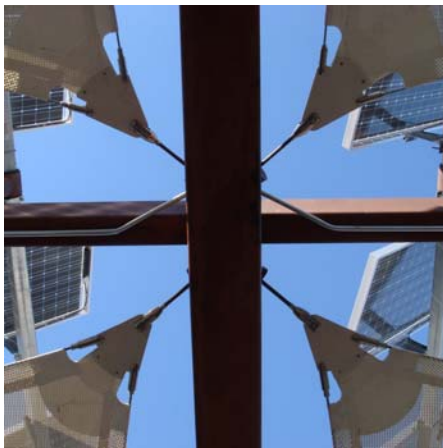


FIGURE 9
Membrane corner attachments



FIGURE 10
Intermediate membrane & valley cable attachments



FIGURE 11
Springs Preserve catenary edges

ACKNOWLEDGEMENT

Burnside Residence

Fabric Canopy Contractor: Rader Awning
Architect: Archaeo Architects
Fabric Canopy Engineer: Huntington Design Associates

Springboro Amphitheater

Fabric Structure Contractor: Glawe Awning
Fabric Membrane Manufacturer: Eide Industries
Architect: Lorenz & Williams
Fabric Structure Engineer: Huntington Design Associates

Springs Preserve Photovoltaic Structures

General Contractor: Sunpower
Fabric Canopy Contractor: Eide Industries
Architect, Mechanical & Electrical Engineer: Sunpower
Steel Structure Engineer: Material Integrity Solutions
Fabric Structure Engineer: Huntington Design Associates

