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Design of Connections for Tensioned Fabric Structures

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Introduction

This paper is excerpted from the chapter on connection design in the draft report of the Tensioned Fabric Structures Task Committee. The full chapter contains additional commentary regarding the detailing of supporting masts and other forms of pretensioning mechanism.

Tensioned fabric structure connections must satisfy a range of parameters that makes their design uniquely challenging. These include the following:

1. Load Transfer. Most load is delivered to connections via steel cables that carry large forces in very compact areas. Connections must resist these high load densities and provide a path for the forces to flow to grade.

2. Displacement & Rotation. The high flexibility of fabric structures results in displacements and rotations under load that are very large relative to conventional structures. Connections should be detailed to ensure that proper flexibility exists to accommodate anticipated movements. This requires that rigid connecting elements either be isolated from the fabric or shaped to avoid damage to it, and that cable anchorages accommodate movement without kinking or otherwise damaging the cable. Where required, connection points must also retain weather tightness under expected movements.

3. Adjustability. Some fabrics in common use will experience creep elongation under long term prestress and transient loads. These elongations must be considered in both patterning of the membrane and in connection design. Creep results in the loss of membrane prestress, which may in turn cause unsightly wrinkles and allow wind flutter to occur – conditions that may lead to damage of the fabric. If not accounted for, creep may also lead to connections with unbalanced loading and unwanted displacement. Where creep is a concern, selected elements of the structure must be designed to allow adjustment. Typically, this is accomplished by adjustment of the mechanism that was operated to create the original membrane prestress.

4. Assembly. Field assembly of shop fabrications typically requires joining highly flexible elements subject to large movements, while working from man lifts or rigging high above grade. In addition, the damageability of the fabric generally makes field welding of steel supports problematic once the membrane is in place. These constraints dictate the use of simple bolted or pinned details for most field connections.

5. Durability. Where connections are exposed to weather, care must be taken in their detailing to avoid corrosion. A variety of means of corrosion protection are available
that include galvanizing or painting steel, or using stainless steel or aluminum elements. Accommodation should be made for touch up of galvanizing or paint that has been damaged during construction.

6. Fabric roofs generally lack ceilings or other elements to hide the roof structure, and structural connections are therefore typically visible from inside the building. The visual elegance and expressiveness of exposed connections is critical to the aesthetic success of fabric structures, and necessitates unusually close collaboration between architectural and structural designers.

Each fabric structure has unique connection requirements, and most connection designs provide for more than one technically acceptable solution. The commentary and schematic details that follow show or describe only the most common solutions to typical connection problems. The most successful structures employ connections designed to provide simple and direct load paths and a visual expression of the flow of forces that is intuitively clear to both designer and layman.

**Fabric Joints & Terminations**

**Fabric to Fabric Connections**

Fabric membranes are supplied in roll goods of varying widths. Patterns are then cut from the roll goods and the patterns are assembled together at the edges by heat sealing, gluing, or sewing to produce the final assembled fabric structure.

Membrane stresses must be transmitted through the fabric seams without creep, separation, or tearing. Typically, seams are created by lapping and fusing the membrane material to itself, and seams are generally designed to carry load up to the full tensile strength of the fabric. Seam strength is primarily a function of coating adhesion (for glued and welded seams) and seam width. Fabric seams and splices should be arranged shingle fashion for optimal shedding of water.

Depending on the logistics of erection, field seams may be made either on the ground or in place atop the roof’s supporting structure. Roped fabric edges secured between clamp plates are used most often, and may be aligned with ridge or valley cable locations (Figure 1).

![FIGURE 1 – FIELD SPLICE](image)
**Fabric Termination at Rigid Edge**

Termination of a fabric membrane at a rigid edge condition, such as a concrete or steel curb, is usually accomplished by a fabric roped edge and clamping hardware (Figure 2). Clamping hardware is typically anodized or powder-coated aluminum, which can be cut, bent, and radiused to protect the fabric with relative ease, and is used in combination with stainless steel fasteners to avoid corrosion problems. The fabric terminates at a “rope” that is sealed inside the fabric edge to prevent it from pulling through the clamp bar.

![FIGURE 2 – EDGE CLAMPING](image)

**Fabric Termination at Cable**

Where the fabric membrane terminates at a catenary cable edge, the fabric to cable connection can be accomplished most simply by enclosing the cable within a fabric cuff which transfers the membrane stresses uniformly along the length of the cuff, as in Figure 3. The cuff material is generally cut at a 45 degree bias to the main fabric panel so that it can be curved to fit the line of the cable without wrinkling.

![FIGURE 3 – CABLE CUFF](image)

The cuff must be sized so that cable termination hardware will slide through it without binding. A small diameter rope installed into the cuff when it is fabricated can be attached to the cable fitting to facilitate pulling it through the cuff. Alternatively, a fabric roped edge can be compressed between clamping hardware, with the clamping hardware attached intermittently to the cable by means of straps, as shown in Figure 4.
Where field assembly of sectionalized membranes is required, the two sections can be attached to either side of the cable by installing clamp bars and straps to both sides of the cable.

**FIGURE 4 - CABLE CLAMPING**

**Fabric Termination at Corner**

There are special detailing problems associated with the termination of the fabric at “corners” - those locations at the edges of the membrane where catenary cables terminate at masts or other supporting elements. Small errors in patterning or cable length can have critical effect at these locations, where the fabric necks down to a small width. In addition, tension in the fabric tends to pull it away from the supporting member, causing it to ride up the cables and away from the support. This effect is generally not addressed in currently available software, which assumes that the fabric and cable share the same nodal geometry, such that sliding between fabric and cable is not modeled. The effect can be pronounced when the angle between the two cables is acute. While reinforcement of the fabric in this area is helpful, some supplemental mechanism for restraining the fabric is generally required. Often, the fabric is terminated beneath a clamp bar mounted to a “membrane plate”. The plate typically also anchors the catenary cables at the edges of the membrane (Figure 5).

Preliminary detailing of membrane plate connections is appropriate prior to the completion of final analysis. This detailing should consider the geometric requirements for fabric and cable terminations and the length required for any anchorage adjustment devices, so as to establish the relationship between all cable and anchorage worklines. Changes in the ratio between element forces under load will cause the membrane plate to rotate under various load combinations, and analysis can determine whether these rotations will cause unacceptable local stresses in cable terminations, anchor rods, or the membrane plate. In Figure 5, for example, increase in the force in the catenary cable towards the top of the figure relative to the force in the catenary towards the bottom of the figure will cause the membrane plate to rotate in a clockwise direction.
Membrane plate connections are important visual singularities that deserve careful attention to aesthetics. In Figure 5, fabrication expediency would suggest a triangular membrane plate, with straight edges between the catenary cable and anchor rod terminations. Necking these edges inward, as shown, provides a connection of greater elegance, with a lightness in keeping with the general character of the membrane structure as a whole.

**Fabric Support at Rigid Element**

Where fabric relies on a cable or steel member for support, it is usually carried by, but not attached to, the member. Often a seam is placed to coincide with the member in order to minimize the seam’s visual impact (Figure 6). If not, and if the supporting element (generally a cable) is small, a bias wear strip can be provided. Plastic coated cables are preferred; however bare cables can be used when enclosed in a protective fabric cuff.
If analysis indicates that the fabric may lift off of a supporting arch, it may be necessary to attach the membrane to the arch with a cuff or by clamping the fabric along its length to control deflections and membrane stresses.

**Cable Saddles & Terminations**

The primary detailing problems of cables used in tensioned fabric structures are termination at the cable ends and saddles that support the cable at angular changes created by intersecting elements along its length.

**Cable Termination Hardware**

Cable terminations must transmit cable tensile forces into the supporting structure. They may either be fixed or allow adjustment in cable length, and they may allow the cable to articulate through angle changes about zero, one, or two axes. A range of hardware is available to satisfy these requirements that varies in adaptability, economy, and visual elegance.

The most economical termination is a looped cable eye formed by a thimble and secured by U-bolted clips. Eye terminations provide for wide rotation about both axes, and can readily be made either in the shop or in the field. Their application is limited by their inelegant appearance and potential for improper installation, but they are suitable for temporary structures or those with limits on budget or need for sophistication. Swaging sleeves may be substituted for cable clips to enhance their appearance and reduce the potential for damage to the fabric from the exposed clips.

Cable eyes may be interlocked with one another to splice two or more cables together, and the eye ends of one or more cables can be linked with shackles to provide attachment to ear plates welded to the supporting structure. The thimbles used in cable eyes force the cable to a tight bending radius, and the designer must reduce the allowable cable capacity as recommended by the manufacturer or validated by testing.

Swages and spelters provide reliable fixed-length cable terminations that are generally more expensive, less bulky, and more sophisticated in appearance than eyes. In swaging, the fitting is clamped tightly onto the end of the cable. Spelters are formed by pouring molten metal inside a tapered sleeve as required to fix a cable whose wire ends have been spread open inside the fitting.

Both swages and spelters are available with stud ends, which are male threaded terminations that provide adjustment in length. Stud ends may be fixed against rotation by installing a nut to either side of the attachment plate, or they may be allowed to rotate about both axes when a nut is installed only on the bearing side of the plate. Where necessary, rotation capability may be enhanced by the use of spherical bearing washers. Swages and spelters are also provided with jaw ends (which attach to a single ear plate with a pin), and closed ends (eyes that may be secured between pairs of plates or onto clevises). Jaws and closed ends allow rotation about a single axis in line with the center of the pin or eye hole, although pairs of shackles may be added to permit rotation about both axes.

Stud ends can be detailed to allow cable length adjustment, as discussed above. Cable length variation may also be provided by splitting the cable into two segments
joined by a turnbuckle. Some proprietary jaw terminations also have threaded elements that permit limited adjustment.

**Cable Termination Design**

All of the terminations described above typically attach to steel plates which are in turn attached to steel supporting members. These “ear plates” to which jaw, eye, or clevis terminations are attached must be sized with thickness and edge radius adequate to prevent both bearing failure at the pin and shear or tension failure on the net section of the plates adjoining the pinhole. Where the width of opening in a jaw-type fitting is substantially larger than the thickness of the ear plate, washer-shaped “boss” plates are welded to each side of the ear to match its thickness to the width of the jaw and prevent bending of the attachment pin (Figure 7).

At mast tops or other critical locations, multiple cables often connect at a single workpoint. Where this occurs, the connection geometry must provide necessary clearances between adjoining cable terminations and plates to facilitate installation and to allow for all displacements and rotations anticipated under load. Where possible, ear plates are configured so that the worklines of the supporting member and attached cables all coincide, and bending moment is not introduced to the member. However, it is sometimes necessary or appropriate to offset cable workpoints at a connection to satisfy geometric constraints, and both member and connection design must consider bending effects resulting from such offsets.

The attachment of ear plates to supporting members induces local bending moments, particularly in thin walled pipes or tubes. The connection design must consider these moments, and adjust connection geometry or add reinforcing plates as required. Several approaches are possible:

1. At lightly loaded ear plates, or where supporting member walls are stout, ears may be welded directly to the outside face of the member.
2. Ears with intermediate force levels may be knifed through the supporting member to allow welding at both faces of the member.
3. Where force levels are high or where multiple ears make knife plates impractical, ring plates at the top and bottom of the ear may be utilized to reduce local bending and punching shear stresses in the supporting member.
4. Where forces are high but ring plates are unacceptable for visual or other reasons, ear plate connections may be devised in which the supporting member is cut into sections to allow the insertion of internal stiffening plates, then welded back together to leave only the ear plates visible.

The design of successful ear plate connections requires attention to resolution of forces, geometric conflicts, cable rotation under load, and aesthetics. Complex connections may also require ingenuity to resolve conflicting issues. A typical ear plate connection utilizing ring plates is shown in Figure 7.
Cable terminations are typically exposed on either the interior or exterior of the structure, and successful design of terminations and the supporting plates and members to which they attach must therefore respond to both technical and aesthetic requirements. Cable connections must be designed to resist imposed load, satisfy geometric constraints, and accommodate anticipated displacement and rotation. However, the choice of cable termination type (stud, jaw, or eye, and swage or spelter) and material (carbon or stainless steel) should also address considerations of visual elegance and lightness, and the visual congruity of the connection design with other elements of the building of which they are a part. Similarly, ear plate geometry should be designed to achieve compact connections and congruity with the angular geometry and lightness of the cables and membrane.

**Cable Saddles**

Where a cable passes without termination over a supporting member or one cable terminates into a second cable, a saddle is required to guide the cable’s change of angle and control its radius of bend. The primary considerations in designing saddles are the size of the cable and its tensile force, the cable’s range of directional orientation under load, and whether it must be restrained from sliding across the saddle (in order to effectively realize an analytically determined change in cable force in the sections of cable to either side of the saddle).

In general, the large bending radius required for structural strand precludes its use with saddles, and wire rope is used where saddles are required. Bending a cable across a saddle causes a stress concentration in the cable, and its allowable load must therefore be reduced. The reduction is generally a function of the radius of the saddle relative to the radius of the cable, and required reductions are defined by ASCE19 and other standards.

Changes in the orientation of the cable under load must be considered in saddle design to assure that the cable does not bear against sharp plate edges that might cause damage under load. The saddle may also require some form of “keeper” to prevent the cable from popping out of it during erection or under extreme loading.
Where analysis indicates a substantial variation in the cable tension on the two sides of a saddle, some means of restraint must be provided to prevent the cable from sliding across the saddle. Moderate resistance to sliding can be provided by clamp plates or U-bolts, though these must not be installed in a manner that distorts the cable cross section and causes damage. Resistance to large differential forces on the two sides of the saddle may require the use of swaged sleeves or similar positive restraint to one or both sides of the saddle.

Some fabric structure designs require that a ridge, valley, or other cable terminate into a catenary or other continuous cable. At these connections, the discontinuous cable will typically terminate with a jaw or eye end fitting pinned to a saddle over which the continuous cable can ride (Figure 8).

FIGURE 8 – CABLE SADDLE AT RIDGE/CATENARY INTERSECTION

Cable Pretensioning Mechanisms

Tensioned fabric structures derive their distinctive appearance, stability under load, and even their name from the presence of consistent pretensioning in the fabric membrane. Pretensioning mechanisms should allow for relative ease of force application, and should accommodate retensioning or release of tension when required to adjust for fabric membrane creep or the requirement that a structure be erected and taken down repeatedly. Pretensioning mechanisms also generally provide a range of positioning to permit deviation from design workpoint locations when required to achieve appropriate tension levels. Well designed tensioning details result in structures that are straightforward to erect and, when left exposed in the finished roof, are elegant and expressive of the flow of forces in the tensioned roof.

Pretensioning can be achieved by pulling the fabric directly to a fixed edge, by manipulating the geometry of masts or other support members, or by pretensioning at cable anchorages. In one such cable pretensioning system, shortening perimeter tieback cables by adjustment of a turnbuckle pulls back on perimeter supports posts; this in turn tensions the catenary cables at the edge of the fabric and draws the fabric itself into tension (Figure 9). Tieback cable tensioning devices are readily applicable in structures where the fabric terminates in a perimeter mast system, and where the obstruction at grade created by the tieback cables is acceptable. Alternatively, pretensioning may be
induced at catenary cables, where, by operating a threaded cable ear plate connector, the cable attachment points are pulled outward to elongate the catenary cables and thereby bring tension into the membrane (Figure 10). Because the entire roof may be tensioned by making adjustment at only a few locations, both types of cable tensioning systems have an advantage in ease of erection over direct tensioning of the fabric.

FIGURE 9 – TIEBACK CABLE TENSIONING MECHANISM

FIGURE 10 – CATENARY CABLE TENSIONING MECHANISM