Chapter 5

DETAILING AND CONNECTIONS

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5.1 Detailing Principles

Developing the design of a membrane structure is an iterative process in which both the overall design and the detail are developed simultaneously. Detailing involves considering the connections of different parts of the structure, while remaining aware of its general evolution. A detail expresses both its function and how the whole structure works. It may also reflect the budget of the client and the experience of the designer. A detail must work in a way that is consistent with the designer’s modelling of the structure, whether physical or numerical. Details must be installable as well as able to function satisfactorily throughout their lifetime. Details generally are vital to the overall stability of the structure although some may be of only minor importance.

A general view of the whole design is needed so as to decide on the “readability” of the structure, to ensure that daylight gets into the space, and to determine the visual quality of all the elements. In this very early stage the general character of the detailing needs to be decided upon as well as that of the overall structural system.

During the past fifty years the technology of tensioned membrane structures has developed a large vocabulary of structural details. Much of this has been recorded comprehensively in Bubner\(^1\). However the technology is still relatively young compared with that of conventional building. More and better membrane materials are being developed and there remains much to be done in refining and developing connection details, opening mechanisms, structural supports and anchorage systems. The current vocabulary is underpinned by the following seven factors:

5.1.1 Following Direct Load Paths

Tensioned membrane structures are stable due to their doubly curved forms generated by tensile force equilibrium. The detail elements must follow this principle and be able to respect the load path geometry as external loading conditions change.

Structural connection elements invariably receive membranes and cables coming from different planes and angular orientation. The design and execution of such elements need to be precise and in accordance with the membrane geometry. Eccentricities must be avoided in order to guarantee the correct shape of the total system. The formations of wrinkles and bad structural performance are some of the consequences of detailing based upon the wrong geometry.

5.1.2 Flexibility for Displacements

The displacements of tensioned membrane structures produced by external loads are relatively large compared with those of more conventional building systems. This characteristic has to be considered during all stages of the design of tensioned membrane structures. Details should allow for displacement and rotation, the magnitudes of which are calculated during the design process, as well as their precise position, direction and angular orientation.
In the course of installation, particular movements and rotations can be required at the connection points. Quite often such displacements are different to those needed for the structural behaviour once the final position has been reached, but still need to be accommodated in the final element so that the structure can be assembled and prestressed.

5.1.3 DETAILING: GEOMETRY, SHAPE AND DIMENSIONS

Prefabricated membrane panels will develop into their intended shapes as a result of forces being applied at a particular set of points. Details and connection points should follow exactly the system line geometry of the suspension points. According to their size, they will take up part of the structure's curvature. Therefore stiff elements like steel plates should be avoided, or their use limited as much as possible, so that the membrane arrives as closely as possible to its suspension points. Membrane structure details should be simple, flexible, of minimal configuration and expressing their own textile characteristics that are so different to other building technologies. Details should also be in scale with the structure and in character with the material used.

5.1.4 INTEGRATION OF BUILDING SERVICES

In tensioned membrane buildings the membrane is the protagonist of the architectonic space; understanding this is vital to securing the building's aesthetic qualities. Consequently great care has to be taken during the design phase to think of how building services, such as artificial lighting and ventilation, can be integrated within a membrane enclosure since suspended ceilings are not often used. Devices for building services should be kept to a minimum and supported independently of the membrane surface. The membrane can be used to good effect for indirect lighting when “uplighters” are used. Such items can be integrated with the landscaping at ground level or, alternatively, fixed to mast supports.

5.1.5 STRENGTH, STABILITY AND DURABILITY

Strength, stability and durability are basic structural requirements for all building systems. For membrane structures it is also the quality of the detailing that guarantees good structural performance. Membrane technology is a “soft” technology and the details should be designed to allow for the flexible behaviour of the fabric including its reinforcements. They should be fluently integrated into the geometry of the system. Discontinuity of membrane forces in the prestress-only condition, as well as in the deformed state, can easily cause material fatigue and should be avoided. This is particularly true at rigidly held edges.

5.1.6 STRUCTURAL INTEGRITY

Despite their very high tensile performance 1mm thick membrane skins are by their nature susceptible to vandalism. Designs have to be such that in the event of the failure of one or more membrane fields within a roof, the whole system does not collapse, and heavy elements such as masts are arrested by a fail-safe system.

Damage should not be disproportionate to its cause and security elements may need to be added into the structure's system. Often they consist of cables that connect the main sup-
porting points, e.g. mast heads. Such elements may not have an active function day-to-day, but they serve to avoid big displacements of the overall structure in the case of the loss of a membrane panel, or the collapse of a support. The membrane itself does not represent quite the same degree of danger in such a situation because of its low self-weight. As a further security measure, fail-safe cables can be arranged to run inside pockets welded to the membrane without influencing the flow of forces through the membrane.

5.1.7 PRETENSION AND ADJUSTABILITY

The dimensions of the individual panels of cloth which are to form the membrane are reduced by a small percentage (“compensation”), such that when the whole membrane is stretched into position the intended prestress field will be developed. The compensation in size should be geometrically similar to the designed form. During the installation of the membrane, temporary equipment such as hydraulic jacks are needed to develop the intended prestress. Such jacking forces are mainly applied in the corner points of the membrane edge and at internal suspension points, or mast and anchor cable footings. Fine adjustments can then be applied where necessary by devices distributed amongst strategic points so as to provide a uniform adjustment of the membrane’s tension.

Changes in strain occur during the membrane’s installation. These changes are related to the membrane’s properties. They are taken into account in the structural calculations and compensated for in the cutting pattern design. After the structure has been in service for some time retensioning may be needed due to residual material deformations (see Chapter 6). The design of the details needs to anticipate such a process.

5.2 SEAMS

Seams are the linear connection between adjoining panels of membrane. The most commonly used is the simple welded overlap. In practice two types of material are very commonly used – PVC coated polyester and PTFE coated glass. The methods for joining them are well established. The strength and serviceability of the seam remains the responsibility of the fabricator, who has also to test the strength of the seam in advance as well as during the fabrication process.

5.2.1 STITCHED SEAMS

For tensioned fabric structures stitched seams are generally limited to the connection of specific parts, and are often used where no other solution is available. Stitching can be used for high loads especially when a PTFE yarn is used. The yarn is UV resistant and an A2 fire retardancy can almost be reached. It is however very expensive and an experienced machinist is needed to adjust the stitching machine.
Stitched seams are produced by an industrial stitching machine with one or two needles. There are many types of stitched seams, their particular use depending on the application. Stitched seams are:

a) mainly used for non-coated fabrics or non-weldable fabrics  
b) not inherently waterproof so need to be covered or impregnated  
c) generally suitable for lower stresses  
d) used when loads are perpendicular to the plane of the membrane. This is often the case with air inflated systems.

The principle parameters affecting seam strength are:

a) the distribution of the stitches (number of stitches per cm)  
b) the yarn stress (the stronger the yarn, the stronger the connection can be)  
c) the arrangement or pattern of the stitch (zig-zag or straight).

The best seam for a special material can be determined by testing. By analysing the failure process, the parameters needing modification can be found. ISO 4915 and ISO 4916 have information on stitching.

5.2.2 WELDED SEAMS

Welded seams are most commonly used because of their inherent watertightness and the controlled production processes employed. Welds are generally made by the simple overlapping of panel edges. The width of the overlap determines the width of the weld. The welding process fuses together the coatings of the two overlapping pieces of material. This is an important difference with stitched seams. Stitched seams have a mechanical connection between the two cloths.

The strength of a welded seam depends on the bonding of the coating to the weave and the width of the seam. By changing the width of the seam, the strength of the seams is changed.

For PVC coated polyester fabrics (e.g. polar materials) the following methods are available:

a) high-frequency welding, shop only  
b) hot wedge welding, shop only  
c) hot air welding, shop and site. Hot air welding needs an experienced manufacturer and is most appropriate for straight seams. It is not recommended for permanent structures. It is possible to apply on site but on condition that a clean and dry environment is available.

For PTFE coated glass fabrics:

a) Heat welding process in the shop  
b) Heated irons, hand held, for site patch repairs.
There are different types of construction for welded seams as shown in Fig. 5.2.

The most common seam is the overlap seam followed by the butt seam. In seams the force has to be carried from one fabric to the other by means of the coating. In some cases of PVC coated polyester a top lacquer has to be ground off prior to welding.

The strength of the seam has to be investigated by means of uniaxial testing. Currently there are no specific codes for testing seams for tensioned membrane structures. Codes like DIN 53 357, NF G 37 107 provide tests relevant to the clothing industry. For example the T-Test investigates the seam under a “peeling” load, whereas membrane structures are designed so as never to be loaded in such a way. The test gives information on the adhesion of the coating to the weave but has no connection to a practical loading case.

For the results of seam tests not only the seam strength but also the failure mode should be taken into account. A test can be used if there is a failure of the material close to the seam. Close to the seam the stresses in the fabric are doubled – the so-called “stress singularity”. When the bonding to the weave is not enough for the connection, the coating will come loose from the fabric – the so-called adhesion failure. When the weave itself loses its connectivity it is called a composite failure.
Because the coating is the connecting element in a seam, and can be influenced by temperature (up to 70°C on PVC coated fabrics is possible outdoors), joints have to be tested under elevated temperatures. The usual failure under temperature is the adhesion or shear failure.

Manufacturing controls are vital to maintaining the quality of seams during production. Welding parameters need to be set and tests made before production commences each day. (Chapter 10 describes fabrication processes and controls.) The strength of a seam increases with its width up to a maximum value, which is generally referred to as the “optimum seam width”. This width can be determined by uniaxial testing.

Seam tests are usually done for symmetrical seams; these are mainly found in the centre of large structures. “Symmetrical” in this case means that the directions of anisotropy (warp and weft) of the connected cloths are largely parallel with one other.

It can be worth determining how seam strength changes within the included angle between the mean axis of anisotropy (warp- or weft-direction), because at the edges and in smaller structures larger angles occur.

Currently the angle is just taken into account as a limited angle depending on the material. This angle can vary but an indication of the value is about 10 degrees.

There are differences between symmetrical and unsymmetrical seams in the manufacturing process. In case of an unsymmetrical seam, registration marks have to be set, and a different compensation has to be applied.

Humidity and temperature both have effects on seam strength.

5.2.3 COMBINATION SEAMS

Seams which use a combination of both stitching and welding can provide an extra level of security in, for instance, for hot countries where fabric temperatures can approach 70°C. After stitching, a seam can be covered with an extra layer of fabric, to make it watertight and protect the stitched thread from UV. This layer does not make the seam stronger, but makes it safer. The strength of a welded seam is much lower at higher temperature due to weakening of the coating. Providing an extra stitched seam guarantees a greater strength. Also the combination seam provides useful resistance to forces applied at 90° to the seam edge which could otherwise cause a “peeling” failure.

Combination seams are of course more expensive than simple overlap welds and only apply to stitchable materials – for example PVC coated polyester and woven PTFE cloth but not PTFE coated glass.
5.2.4 GLUED SEAMS

Glued seams are not commonly used in membrane structures. Glueing is used in making patch repairs to PVC coated membranes but is expensive and labour intensive. Elastomer coated materials like Hypalon or Silicone coated fabrics are connected by gluing or stitching.

A double-sided adhesive tape has been developed recently for joining panels of silicone coated glass. Once applied, the adhesive is activated by means of heat (± 200 °C) and pressure. This two-step procedure allows the possibility of adjusting the panels before activating the adhesive.

5.2.5 LACED SEAMS

Lacings are used to connect two parts of fabric in an easy and demountable way. The lacing consists of a piece of rope connected to one part of the fabric and by means of particular ways of lacing connections can be made. There are several methods most of which originate from the traditional travelling circus tent (Figure 5.6). The load carrying capacity of such connections very much depend on the reinforcement of the holes through which the lacing passes.

5.2.6 CLAMPED SEAMS

A clamped seam is made by a series of shaped, overlapping plates that are clamped together through the fabric by bolting. The strips are made in discrete lengths depending on the curvature along the seam. They also need to allow for straining of the fabric that constrains them in length (Figure 5.7).

This type of connection is installed on site, has a strong visual appearance and is used to join large prefabricated membrane panels together. It can be made out of a variety of materials capable of taking the load e.g. wood, steel, aluminium.
Clamp plate connections can be used for subdividing very large fabric fields to ease handling in the shop.

A single layer of clamp plates can be used in a similar way to clamp a membrane edge directly onto a beam boundary.

The connection depends on the “keder” (also known as a “bolt-rope”) running along the boundary of the fabric panels. The transfer of load between the membrane and the boundary line of support occurs by the keder bearing against the edge of the clamp plates. The keder prevents the fabric from sliding between the clamp plates. The clamping force should be just high enough to allow the membrane force to be transmitted by bearing of the keder against the edges of the clamp plates. The clamping force should not be so high that the membrane force is transmitted by friction created between the clamp plates and the membrane. The mechanism also relies on the holes through the fabric being large enough to give good clearance around the bolt. Such a clearance has to allow for construction tolerances. The clamping force should not be too high because the bolt is not intended to be the force-carrying element. (Clamping based on friction would only be possible with pretensioned bolts or the use of springs due to creep in the fabric.) The distance between the bolts is related to the out-of-plane stiffness of the clamping plates. The more frequent the bolts, the less the clamping plate stiffness that will be needed. The keder needs to be held continuously along its full length.

Compensation values should be taken into account in determining the gaps between plates. Marks have to be set.
5.3 Edges

There are two types, flexible or rigid, and in either case both normal and tangential forces need to be transferred from the membrane into the edge element or system.

5.3.1 Flexible Edges

Flexible curved edges allow the prestressing of the fabric as the result of a tension force developing in the boundary element. Several configurations are available:

a) A very commonly used method with PVC/polyester fabric is to run a loose cable inside a pocket welded continuously along the membrane edge. Such a pocket can be made in several ways (see Figure 5.9). It is also possible to use this arrangement for panels of PTFE/glass. It is however restricted by the length of the seam. When tangential forces become large, the concentration of such force at the corners becomes critical and it can be better to offset the cable from the membrane’s edge as in (b).

b) The edge cable can be placed outside the membrane edge and linked to it at intervals by a sequence of straps and clamp plates. This option is used mainly for PTFE/glass fabric and also for PVC/polyester where edge spans are larger than 20m.

c) Belts can be stitched or welded along the perimeter. This option applies to PVC/polyester fabric and is used mainly for retractable roofs, umbrellas, small span and temporary structures. It performs the function of taking up edge tangential forces. Woven textile belts can be stitched or welded to PVC/polyester without damage to the cloth. However this is not the case with PTFE/glass, which can only be joined to itself by welding since stitching causes damage to the glass yarns as well as allowing moisture to penetrate the yarns causing loss of strength.

Fig. 5.9 Flexible edges: cable in pocket, cable outside pocket and clamped to the fabric and belt reinforcement of the fabric.
In principle there are two different ways of forming a pocket:

The first is to turn the fabric's edge back on itself and this needs to be done in discrete lengths for the fabric to be able to conform to the curvature of the cable. To do this requires slits to be made in the material at right angles to the cable's axis at suitable intervals depending on the radius of the cable's arc.

The second method is to "pattern" the cable "cuff" to the proper shape such that when the prestress builds up, a smooth shape develops without wrinkles forming.

An important parameter for the strength of the pocket is the angle between the upper and lower surfaces of pocket. This value logically depends on the width of the pocket in relation to the diameter of the cable. This must be large enough to avoid large peeling forces along the line where the pocket is welded to the membrane, i.e. where the upper and lower surfaces of the pocket diverge from one another.

Movements of the fabric along the cable in the tangential direction have to be prevented so as to avoid abrasion damage. In some cases belts are used to carry the tangential membrane forces directly into the corner.

Depending on the membrane material type belts can be joined to it by stitching or welding. They can be attached to the inside or outside of the cable pocket. Belts on top of the membrane have to be covered so as to protect them from UV and to avoid the growth of moss.

Belts have to be compensated for their creep behaviour and require an "initial stretch" before their installation.
5.3.2 RIGID EDGES

Rigid edges are edges where the fabric is held continuously by a supporting structure having much greater lateral stiffness compared with that of the fabric. There are a variety of solutions and the following, shown in Figures 5.12 and 5.13 illustrate the principle types:

a) Tube in a cable pocket (PVC/polyester). The points mentioned for cable pockets are valid here. Forces travel perpendicularly into the tube. Movements along the tube have to be prevented and the angle for the pocket has to be chosen to be small enough to limit “peeling” forces in the seam.

b) Channel (PVC/polyester). The membrane edge is furnished with eyelets at frequent intervals. A rope is laced through the eyelets and around a rod in the channel. Forces are led perpendicularly into the channel, and because of the triangular lacing, tangential forces are taken up too. This is one of the many possibilities for a rigid channel edge.

c) Clamped edges. These are similar to clamped seams but there is only one layer of cloth. They can be used for both PVC/polyester and PTFE/glass.
5.4 Field Supports

5.4.1 Linear Supports

The characteristic property of the “Ridge and Valley” shape (or “Wave” shape) is the direction of its double curvature. Cables running parallel with one another give the wave shape. The prestress in the fabric can be obtained by tensioning the ridge and/or valley cable. The cables need to be adjustable in length.

Linear arches used in different orientations to one another produce different surface shapes as shown in Figures 5.16 and 5.17.


5.4.2 POINT FIELD SUPPORTS

The basic anticlastic shapes of cone, hypar and saddle obtain their surface shape from the relative disposition of boundary supports. Forces developing within the surface ultimately become focused at the boundary supports. Specific detailing is required to enable this kind of support to be effective. A very common way to control the level of stresses in a membrane is by making use of a ring shaped element. The diameter of the ring will depend upon the strength of the fabric and the total load to be carried into the support. The designer may choose to add a reinforcing layer locally to the membrane as a means of reducing the ring’s diameter. The ring can be made of a variety of materials, steel being the most common. There are several ways to attach the membrane to the ring as shown in the accompanying pictures.

To make the ring watertight it can be covered in different ways. Sometimes it is used for ventilation. When the internal support is used as a low point, it will gather rainwater and snow unless drainage is provided.

Another way of decreasing the stress in the fabric is making use of the so-called “butterfly” solution which originates from soapfilm formfinding. A sequence of cable loops form a closed continuous boundary lying within the membrane’s surface. It is an elegant but labour intensive solution.
5.5 Corners

Forces in the membrane flow into the boundary cables which, in turn transmit them to the corners. The corners transfer these forces into the supporting structure. The detail between the corners and the supporting structure is important and can be solved in a variety of ways.

During its lifetime a detail has different functions to perform. Before it gets to site it can be an awkward piece of metal that is liable to damage the fabric if care is not taken in its handling. On site it becomes active in helping to install and prestress the structure. During its service life it must remain active as an articulated part of the structure moving in sympathy with the membrane. In these two phases, it is required to perform different functions.

During installation:

a) Forces initially tend to go through the membrane rather than through the cable. The cables are still slack because the fabric is not in its final position. So the weight of the fabric may be carried solely by the connections of the fabric to the corner.
b) The corner details have a particular mass that has to be taken into account during the installation procedure. Temporary support may be needed to support them and hold them at an optimal angle.

c) Flexible connections are needed to provide enough degrees of freedom during installation because the membrane is not in its final position and at the start of the installation it has a position determined by gravity. This can, for instance, cause a 180° rotation of a corner during lifting of the fabric.

d) Installation devices are needed to enable the lifting, hoisting, stretching and prestressing of the membrane. The corners must be provided with means of attachment.

Functions when installed:

e) Transfer of forces through the edge cable. The forces are not transferred directly into the corner by the fabric, but are essentially passed into the boundary cables that then transfer the forces to the corners.

f) Transfer of tangential forces. A doubly curved membrane has stresses in both warp and weft directions. Stress perpendicular to an edge is transferred into the edge element. The stress in the other direction runs along the edge and needs to be collected at each end e.g. at the corners. When an edge cable lies loosely in a pocket, tangential force can cause movement of the cable in relation to the cable pocket. By providing a means to prevent this movement the tangential force is absorbed.

g) Geometric compatibility. It is essential that after installation all the forces that are collected in a corner are running along their system lines so as to prevent eccentricity and stress concentrations in the corners which, in the long term, could cause failure of the connection.

h) Accuracy in manufacture. Related to (g) above, the design can be according to system lines, but when the manufacturing of the corners is inaccurate the same trouble can arise.

i) Adjustability. To be able to fine tune the membrane during installation or in some cases to prestress the membrane, the corners should be provided with adjustability.