Sample Chapter

Tensile Surface Structures
A Practical Guide to Cable and Membrane Construction
Editor: Michael Seidel

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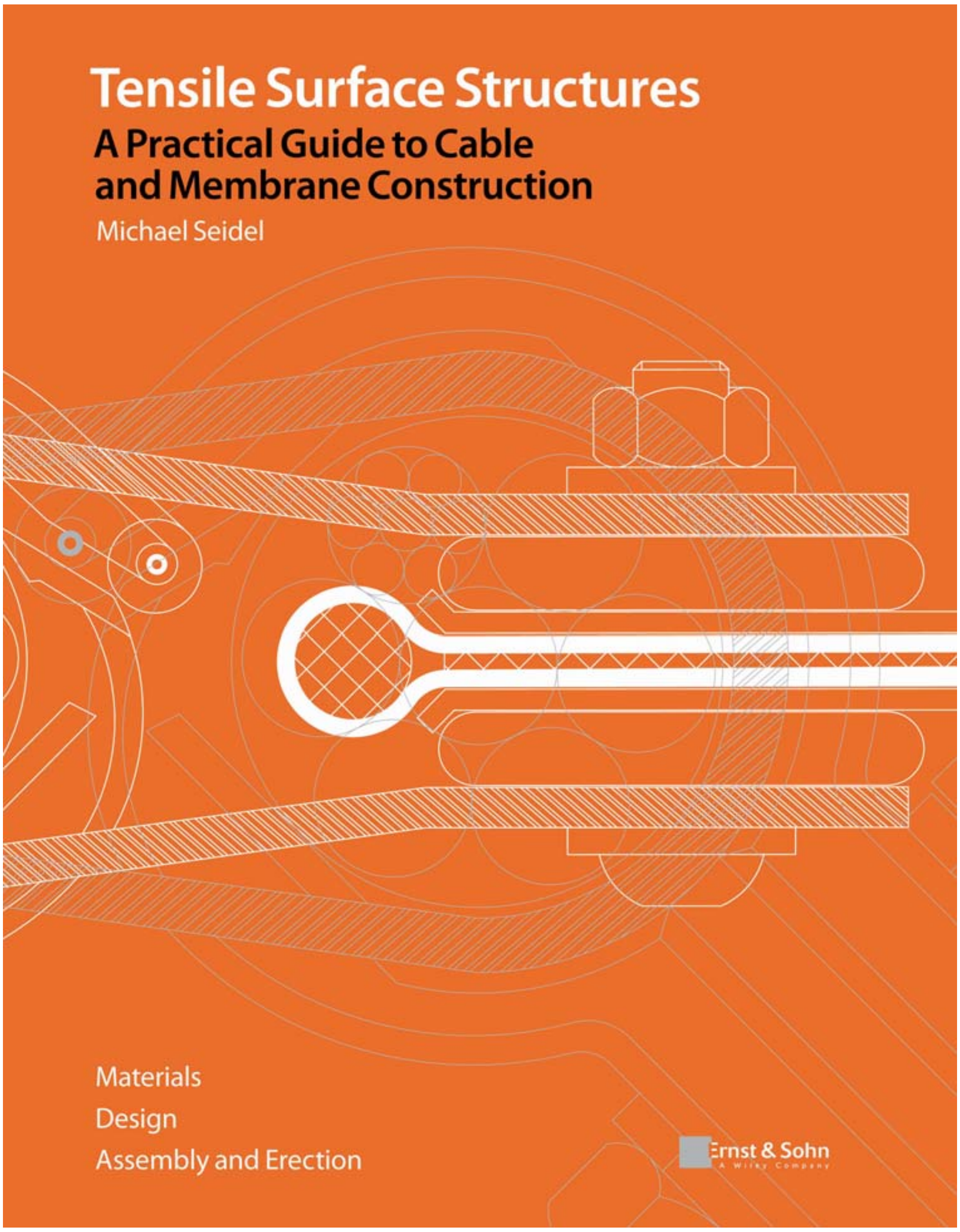

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2.4.3.2 Erection criteria

In addition to the determination of the strip layout favourable for the deformation behaviour according to structural and topological criteria and production limitations like strip width, cutting waste and seamed joints, the division of a membrane surface into strips is also subject to limitations regarding erection. It becomes particularly clear during the tensioning process, how important the material used, its cutting patterns, the shape of the surface and the type of edging are for the erection. This particularly makes the tensioning scheme, which can have a considerable effect on the overall project costs, economically significant in the erection process.

Tensioning travel, tensioning direction – cut-out pattern direction

In order to make a membrane sufficiently load-bearing, it has to be biaxially tensioned in the relevant curve and fixed. The calculated share of compensation must be pulled out of the material through the edging and its corners.

The cost of implementing a tensioning procedure is determined mainly by the arrangement of the individual panels. Apart from the optical appearance of the seams and the structural conditions in a membrane surface, all erection measures, like the dimensioning and installation of the tensioning equipment, measures to stabilise the primary construction and the arrangement of scaffolding, depend on the orientation of the strips.

Because varying forces have to be applied according to the compensation and the length of tensioning travel in order to pull a membrane into position, the cutting pattern direction plays an essential role for the tensioning process. The calculated shortening of the considerably more compensated weft direction is mostly pulled out of the membrane surface out of the long or transverse direction (Fig. 98). To determine the primary tensioning direction, it should be considered how large the force necessary to pull the tensioning travel is and how much the associated erection cost is.

Under the effect of loading, the main anisotropy directions shorten against one another. For the tensioning process, it is thus of central importance how load acting in one fabric direction influences the forces and strains in the other. It will be necessary to reconsider the layout of the strips for surface forms, in which no interaction between the warp (K) and weft directions can take place during the tensioning process.

The use of fabrics with dissimilar stretch properties can be very advantageous for the erection of geometries with different lengths in warp and weft directions. When using such fabrics, the ideal case is to arrange the larger part of the compensation in the weaker weft direction. The strain in the stiffer warp is very slight, and is therefore little compensated. If possible, the strip layout will be arranged so that after testing all the criteria stated above, the desired biaxial pretension will be produced solely by tensioning in the weft direction. In order to build up enough stress in the warp direction by

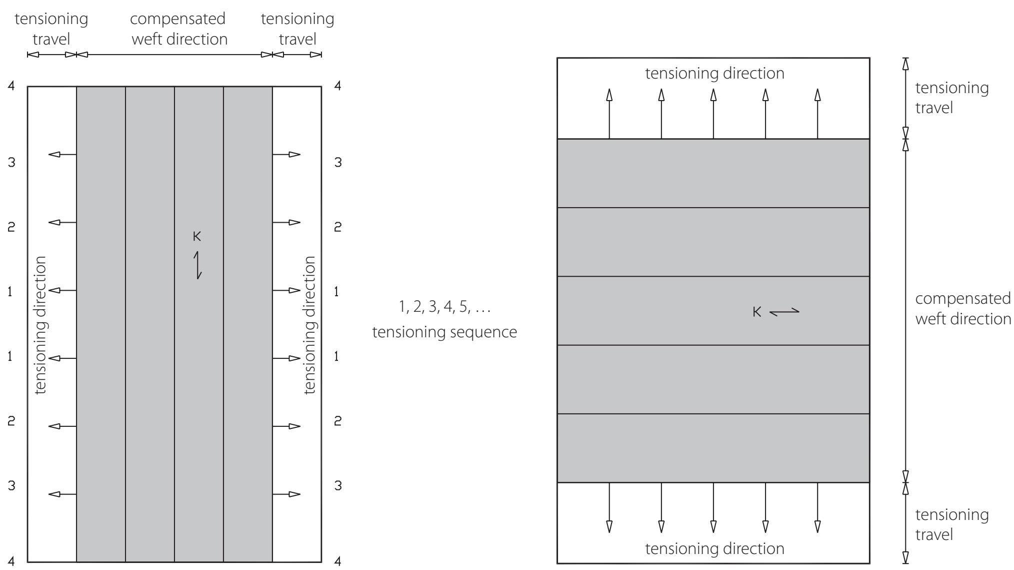


Fig. 98: Diagram of idealised tensioning procedure with limitation of transverse strain

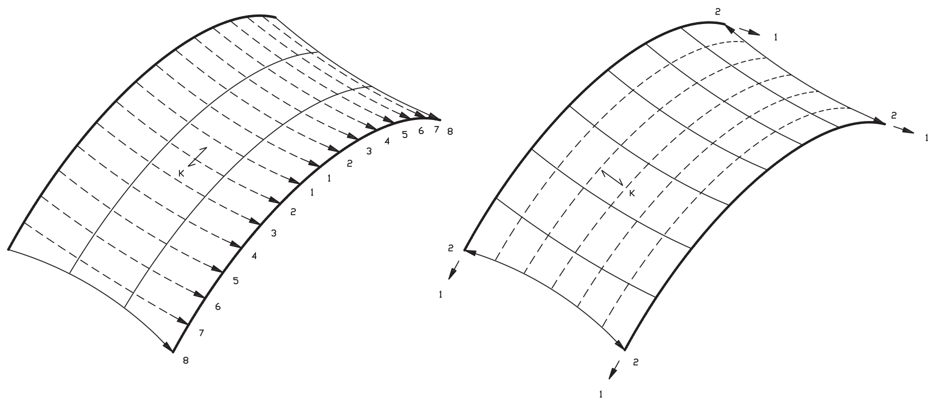


Fig. 99: Tensioning direction and sequence of arched membranes depending on the direction of cutting out

general tensioning in the weft direction, edge deformation perpendicular to the tensioning direction must be prevented. This method of tensioning can be advantageous for erection because working time and pretensioning equipment can be reduced.

If the surface has to be tensioned between two arches, as is often the case with sports stadium roofs, the membrane can be unrolled parallel or perpendicular to an arch-shaped truss. Depending on the material, arch curvature, edge geometry and edge detail, the direction of the strips makes a large difference for the tensioning process and the related measures. According to information from erection companies, there is a considerable scope for saving erection costs here, considering the space taken up by erection equipment.

Fig. 100: Pulling in and tensioning the membrane for the stand roofing at stadium Volkswagen Arena Wolfsburg, Germany

Fig. 101: Pulling in and tensioning the membrane for the stand roofing at Estádio Intermunicipal Faro, Portugal

If a membrane surface unrolled parallel to the arch truss is compared with one unrolled perpendicular to it, then it can be noticed that when tensioning the strips perpendicular to the arch truss (left in Fig. 99), the pretension has to be applied at more points than with the variant (right in Fig. 99). This requires more work and equipment.

Apart from setting up and operating the erection equipment at the location where the force is applied, this extra work is often caused by the type of edge detail.

If the use of single clamping plate edge elements cannot be avoided because of structural requirements, then the forces must be applied starting from the centre and the edge elements installed singly, adjusted and fixed (Fig. 100).

If the warp direction is perpendicular to the arch truss and the surface has the right curvature and has a keder rail edge detail, then the surface can be pulled through the rail and tensioned quickly and easily (Fig. 101).

When tensioning membrane surfaces spanned between two stiff edges, care must be taken with the loading on the seams.

If the tensioning is in warp direction, then the doubling of stiffness along the seams and the welding shrinkage must be taken into consideration. If the direction of cutting out is transverse to the tensioning direction, then suitable measures must be considered to avoid overstressing the transverse seam.

Large distortions are to be expected in the fabric of surfaces with pronounced curvature; the strips must be considerably more compensated then less curved surfaces. This is particularly clear for high point surfaces with heavy fabric. The choice can be made here to arrange the division of strips either with the warp direction of the strips radial around the high point or parallel to the lower edging.

If the stiffer warp lies in the main load-bearing direction, then a much higher compensation of the weft direction is required in order to achieve a uniform stress distribution (left in Fig. 103). A higher force is required there when tensioning to the edges than with parallel strips (right in Fig. 103).[1] Where the strips run parallel to the edging, care should be taken not to overload the seams.

If the tensioning is exclusively by vertical jacking of the high point, then care must be taken that the permissible membrane stress in this sensitive area is not exceeded during tensioning. If the tension is peripheral to the edge, less force is required and the stresses can distribute better in the fabric. The expense of installing stretching equipment along the edges or at the corners can however be expensive.

To determine the primary tensioning direction, it must be considered how large the force required for tensioning is. It is mostly better to pull a membrane surface over a long travel with low force than to pull a short travel with high force. The decision, as to from which direction the shortening is simpler and thus cheaper to pull, thus depends on the strip layout. When pulling over longer travel distances, the strains should be led away from the centre as uniformly as possible. This takes the interaction between warp and weft threads in-

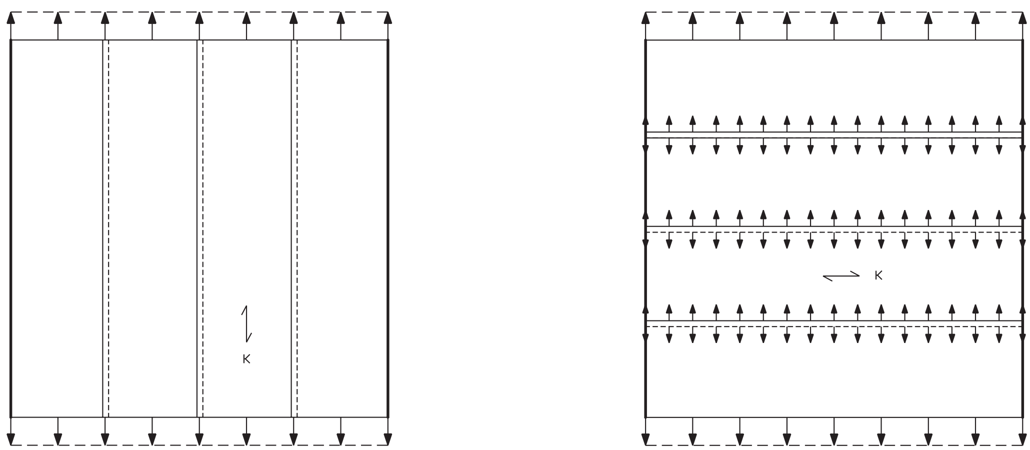
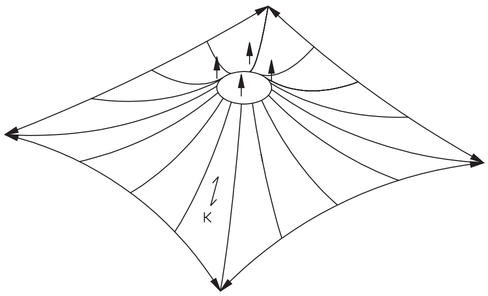


Fig. 102: Seam loading during tensioning

1 *Moncrief, E.; Gründig, L.; Ströbel, D. (1999)*



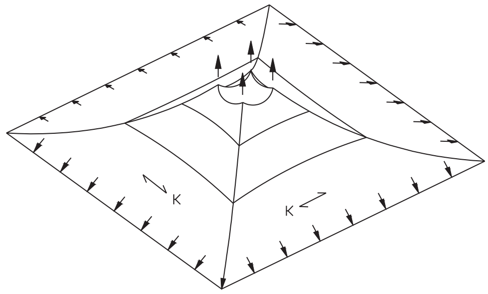


Fig. 103: Tensioning of high point surfaces with different strip layouts

to account; sideways straying of the forces because of force deflection is made less likely.[1]

In cases of topology where the membrane material has to be tensioned over equally long travel distances with the same level of force, the use of fabrics with nearly equal stretching properties in warp and weft directions (Precontraint fabric from Ferrari) can be advantageous for erection. It should, however, be remarked that the force required to span such fabrics is generally higher, making their use less favourable for relatively flat membrane surfaces with low fabric distortion.

If strongly curved surfaces span over large distances, then heavily compensated and long strip lengths are needed. Special care must be taken that sufficient material is available in all areas of the patterned pieces.

Space required and access for carrying out the tensioning

An important practical criterion for the determination of the cutting patterns is the space required during erection for the tensioning equipment, temporary construction and scaffolding. The determination of the strip lengths and and thus the primary tensioning direction also depends, for reasons of practicality, on the types of fixings available for the tensioning devices and temporary construction to be used. In this case, care should be taken with the dimensioning of the erection equipment. A large number of tensioning devices and temporary constructions can take a long time to assemble and cause more working time and high eventual costs.

The strip layout determined as favourable for the deformation behaviour is not always optimal for erection. It can be that the direction of the cut-out strips has to be altered because otherwise the pieces can only be erected with difficulty or not at all. Therefore a workable erection scheme should be produced at the design stage, taking into consideration the provision of sufficient fixing locations for tensioning equipment and their anchorage while tensioning. This shows that the determination of the strip layout also has to consider practical considerations for the tensioning process.

Fig. 104: Tensioning of high point surfaces with different strip layouts

1 *Essrich, R. (2004)*

2.4.4 Cutting out the pieces

Cutting out denotes the division of one or more textile surfaces (layers) according to dimensions or cutting out from pattern drawings as part of fabrication.[1]

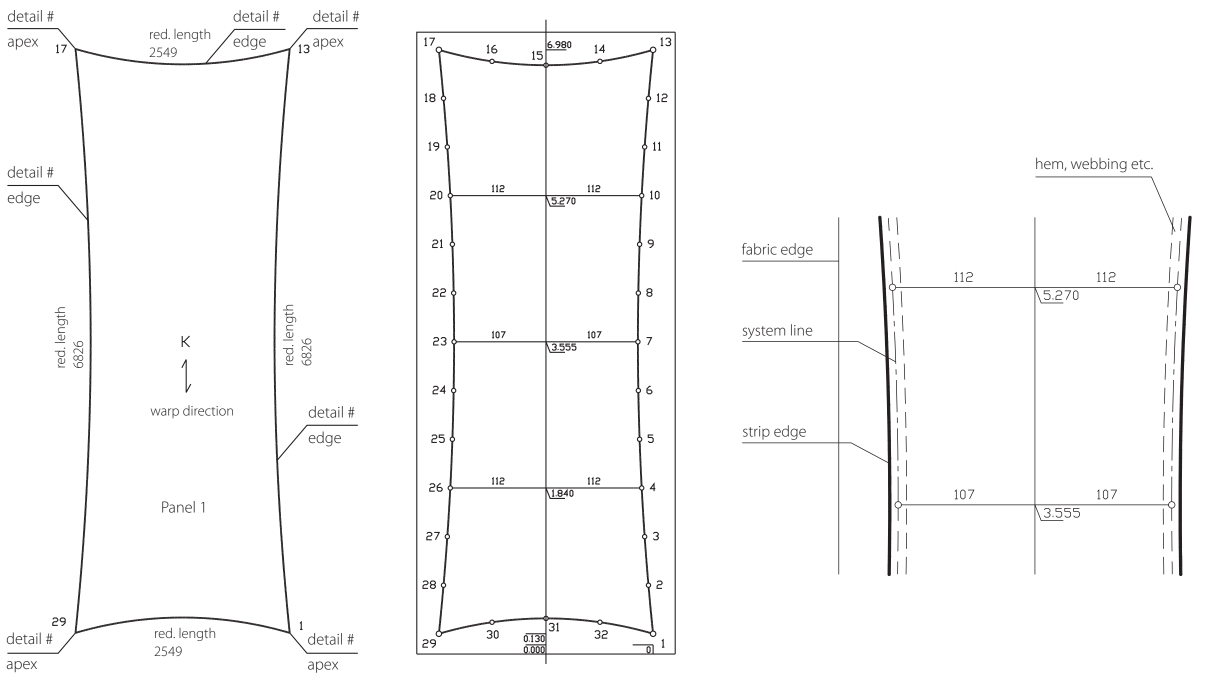
The patterning and design are normally carried out by the engineer. Surface areas, edge details and seams are determined in discussion with the architect. The cutting out of the pieces and the joining, packaging and delivery are undertaken by the fabricator.

The purpose of cutting out is to reproduce the calculated patterning as precisely as possible. This is done by translating the cutting drawings of the individual strips onto the fabric from the roll and cutting the pieces out. The cutting drawings contain the essential specification of the material, the details of the joints and edges and the cutting shapes of the strips. Seam widths and seam allowances are given to enable the strips to be joined, and also length tolerances and production lengths.

The material information contains areas, maximum strip widths and type of fabric. The fabric direction and tearing strength in warp and weft direction are also given.

The type of edge and corner details and the joints in the surface are given in the drawings. There is also a reference to all related detail drawings (a in Fig. 105). Information about the geometry of the pieces to cut out can be read from the drawings of the individual pieces. These also include all coordinates and lengths of the compensated edges. The drawing of the piece is projected by the fabricator onto the fabric material with additional details about cutting waste and the cutting window of the machine (b in Fig. 105). The system lines denote the seam, webbing and rope axes (c in Fig. 105).

To join the pieces, the edges of the strips are marked so that no undesirable folds can occur during seaming, welding or glueing (Fig. 106).



a b c

Fig. 105: Schematic cutting-out diagram of an anticlastic membrane surface

1 *Burkhard, W. (1998)*

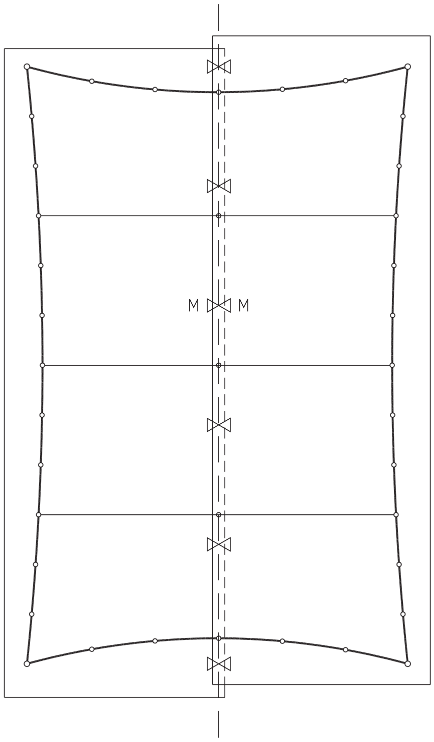


Fig. 106: Marking for the edges of the strip

The cutting out of coated fabrics is either done with hand tools or a cutting machine according to cutting capacity, layer thickness and edge geometry.

Most cutting is done on a machine with defined cutters. Depending of radius, strip length and layer thickness, these can be pull, push, round or oscillating cutters in the automatic cutting process or manual cutting of the layers using hand tools.

Thermic cutting processes are not suitable on account of the risk of the cut edges sticking.[1] The use of laser cutters is also problematic because of the chlorine-air mixture discharged during the cutting process. Ultrasound cutting machines can in principle be used, in combination with a vacuum table, but are not normally economical because of the cost. The use of water jet cutting for the cutting out of fabrics is unknown.

When there are a a number of strips to be cut with the same geometry, pre-cut templates made of thicker material can be used. The strips can be cut out singly or in piles according to the geometry and other requirements. The finished dimensions (cut lengths) must be checked in any case.

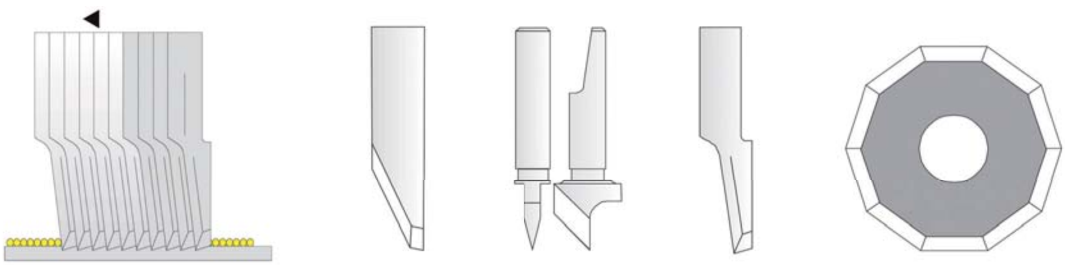


Fig. 107: Cutter tip shapes

Fig. 108: *left, centre:* Mechanical cutting machine with round cutter; *right:* Manual vertical knife machine

1 *Steckelbach, C. (2005)*

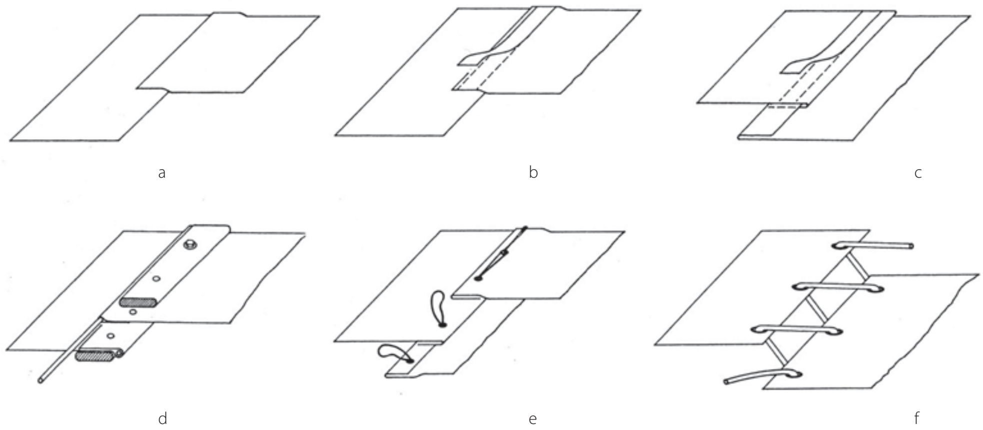


Fig. 109: Surface joint types

a overlapping welded seam
b sewn seam
c lapped sewn seam
d clamping plate joint
e looped joint
f laced joint

2.5 Methods of jointing surfaces

In order to obtain a load-bearing surface, the fabric cut into strips is joined to form panels. Permanent surface joints are made by the fabricator, and temporary or reusable joints are normally carried out on the construction site. The most important joints are:

- Permanent joints – welded seams, combination seams, sewn seams, glued seams
- Temporary or reusable joints – clamping plates and keder rail joints, looped and laced joints

2.5.1 Permanent surface joints

The material cut out from the roll is joined by the fabricator to form load-bearing panels. Various types of permanent joints are used for fabric strips according to material, structural and building specification. These can be welded, sewn, welded and sewn, or glued joints. To ensure load transfer, joints in the fabric must be able to transfer the forces out of the load-bearing threads in the fabric and transfer them to the threads of the conjoined fabric through mechanical joining or bonding. Permanent joints are normally flexible. There are, however, differences of stiffness between the two fabric strips to be joined and the seam. Obstructions to deformation along the seam joint produce irregularities in the overall shape of the membrane. Important factors to observe in the specification of such joints are the different thread locations following from the anisotropic behaviour of the fabric, the adhesion strength of the fabric coating, the seam widths and the seaming or welding process.

2.5.1.1 Welded seams

The welded seam is the most commonly used means of jointing in membrane construction. Welded seams in membrane construction can be produced as overlapping joints with varying overlaps or as butt joints with cover strip. In addition to joints in the membrane surface, welded seams may also be edge sleeve details, reinforcements, keder or webbing seams. Welded joints are normally produced at the works, where partial sheets of up to approx. 5,000 m² can be produced from roll material 5 m wide.

The strength of welded joints depends on welding process and processing temperature and is about 60 – 95 % of the fabric strength. The force transfer is through shear loading of the coating. The quality of the coating and its adhesion to the fabric produce an effect similar to form-fit and determine the strength of the joint. Welded seams produce an abrupt increase in the stiffness at the seam. Welded seams are watertight and normally UV-stable.

The welding of coated fabrics is only possible with thermoplastics. Plastics are poor conductors of heat, so the welding of thin fabrics makes fewer problems than the welding of thick layers. The welding process joins together two or more pieces of fabric of the same material under the influence of heat without the use of additional adhesive. The process can be with or without pressure. The two most commonly used processes for the jointing of coated fabric pieces are high frequency welding and hot element welding. While hot element welding thermally softens the surfaces of the pieces to be joined and presses them together with a defined pressure, high-frequency welding forms a largely homogeneous

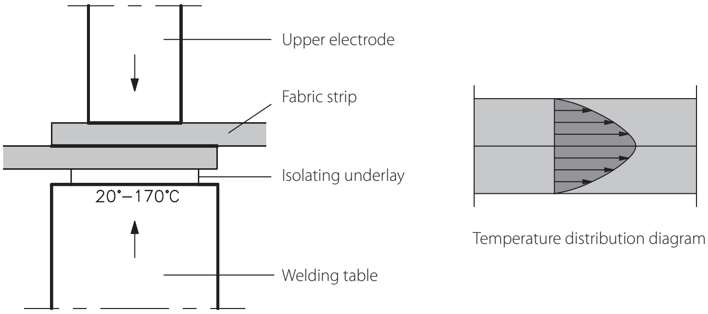


Fig. 110: *left; centre:* Diagram of HF welding; *right:* HF welding plant

joint in which the entire coating thickness of the two material sides to be joined are integrated.

High frequency welding

The cut-out fabric strips (single templates) are joined together in this welding process through pressure and heat. Only thermoplastics with polar molecule arrangement can be welded using this process. If such thermoplastics are placed under a field of high-frequency radiation, certain groups of molecules oscillate according to the frequency, which leads to a warming of the material. The thermoplastic is warmed between a cold and a temperature-controlled electrode, brought to viscose flowing and pressed together (see Fig. 110). After the electricity is switched off, the seam has to cool under pressure in order that the melted mass can harden and the restoring force in the material can no longer become effective.[1]

Because not only the coating but also the fabric are heated, the quality of the joint is dependant on the pressure, the shape of the press, the processing temperature and the welding speed. The average weld seam width is between 50 – 80 mm. A wider seam can increase the strength of the weld for heavier fabrics. When making such wide seams, there can be a problem with the coating "swimming out" from the welding area. This can be avoided through the use of a knurled welding electrode (b in Fig. 111). Full-surface welding in the entire area of the seam can be achieved with a flat electrode (a in Fig. 111). Special electrodes can be used to make intentional breaks in the surface of the seam, which makes the seams more controllable.[2]

PVC-coated polyester fabrics and aramide fabrics welded with the high-frequency process can achieve a strength of about 90 % of the fabric strength at room temperature and approx. 60 % at 70 °C.

Surface paints containing fluorine and laminated foils prevent because of their high melting point a homogeneous connection and have to be removed where the joint is to be

a Flat weld seam | b Knurled weld seam | c Welding bead | c Seam junction

Fig. 111: HF seam types

1 Holtermann, U. (2004)

2 Rudorf-Witrin, W. (2004)

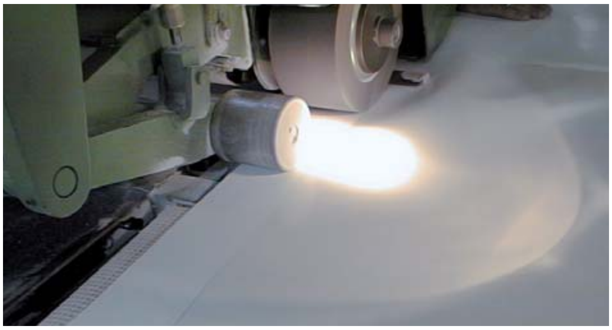


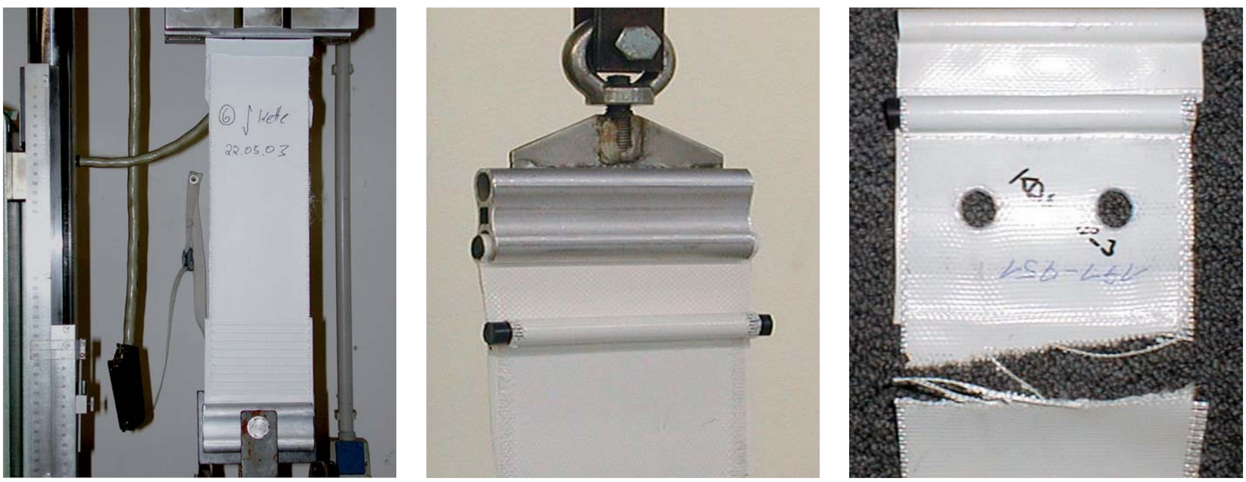
Fig. 112: Grinding off the PVDF paint

Fig. 114: Welding under pretension

made (Fig. 112). Recently available fabrics with modified fluorine paints can be welded together without grinding off the paint, just like fabrics with acrylic paints.

To establish the optimal welding parameters for highly loaded seams, test pieces are prepared in warp and weft direction (Fig. 113). It is especially helpful to carry out such tests on welded-on erection lugs. Control tests are made before every start of work, at the change of shift and when changing the material. If the fabric is welded, then the seam is tested using a scrape test. All the parameters and testing results are recorded as part of quality control. The electronic recording of the welding parameters is helpful, but cannot replace the tear tests.[1]

The heat development during welding produces shrinkage of the weld seam in the long direction. This shrinkage, also called ***thermal crumple***, is compensated during the welding process either by pretensioning the fabric (Fig. 114) or it has to be compensated in a calculation and pulled out of the fabric during erection. The thermal shrinkage must always be taken into account when cutting out.



Control test — Test of the completed seam — Torn seam

Fig. 113: Seam tests

1 *Rudorf-Witrin, W. (2004)*

Fig. 115: PTFE heat welding press with a heating beam length of 2 m and a maximum pressure of 7 bar

Hot element welding

Strips of PTFE-coated fabric can also be welded by heat contact welding, a special form of heating element welding. The coating masses are heated through contact with a heating beam to a temperature of up to 340 °C. PTFE is composed of linear chains and becomes thermoplastic when heated. After the crystalline areas have melted, it is not sufficiently liquid to be processed further. To get round this, a layer of thermoplastic foil is trapped between the fabric pieces to be joined as a welding aid. Then the pieces to be welded are pressed under a pressure of 50 N/cm^2 for 30 – 40 sec. On cooling, a chemical bond is formed between the coatings. This type of joint can reach 80 – 90 % of the fabric strength.

ETFE foils can be welded together thermally using a welding beam or by heat impulse welding. In neither case is a welding aid used. The welding by contact with the beam can proceed continuously or cyclically. Welding is normally done at temperatures above 230 °C.

The crystallite of partially crystalline plastics melts at welding temperature, so the polymer is then available as melted mass. On cooling out of the melted mass, the polymer crystallises again, the density in the crystalline areas increases and the volume reduces. To achieve the required quality of weld seam, rapid cooling of the seam is required after heating. The parameters for the cooling conditions and the tool temperature are according to the experience of the fabricator and have a major influence on the material properties.

The seam widths for cushion applications, depending on the loading, are normally 5 – 20 mm. According to information from the manufacturer, the strength of the seam is about > 90 %.[1]

In thermal impulse welding, the welding heat is produced by electrical impulse in a thin metallic welding band through resistance warming. The welding temperature can be regulated precisely. High seam strengths can be achieved by subsequent cooling under pressure. The advantage of this process is the rapid cooling of the heating bar.

Fig. 116: Welding of ETFE foils

1 Fitz, H. (2004)

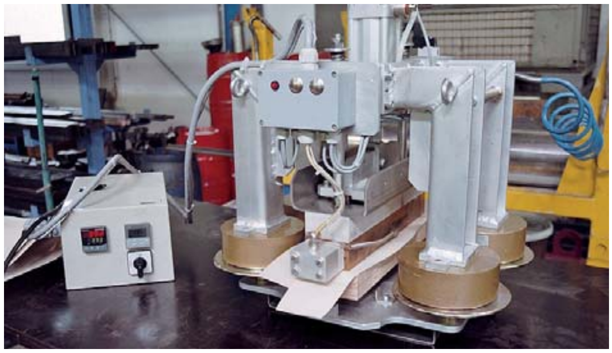


Fig. 117: *left:* Manual welding device; *right:* Mobile magnetic welding device

Welding work on site

For waterproofing and for touching-up and repair work to damaged fabrics, welding must often be carried out on the construction site. Various hand welding tools are used for this purpose.

The site welding of covering membranes made of Glass/PTFE fabrics is now mostly done with hand devices, which apply the pressure onto the fabric with a hand iron. The fabric pieces to be joined, with the welding aid, are welded together at a temperature of about 360 – 420 °C under pressure. This process lasts about 1 – 2 minutes per weld. Devices in use today have a temperature control for a range up to 450 °C (left in Fig. 117).

To weld Glass/PTFE fabrics, magnetic welding devices can also be used. These devices work at a welding temperature of up to 390 °C, are equipped with a heating beam and have a similar pressure to stationary welding presses. They do, however, weigh about 50 kg and are therefore only usable for mobile site welding if hung from a crane (right in Fig. 117).

Waterproofing and repair work on PVC-coated polyester fabrics are usually performed with a hot-air pistol (left in Fig. 118), a welding process that was also formerly used for fabrication. It is possible to work at a temperature range of 50 – 600 °C with the hand devices, which weigh approx. 750 g. The welding of Glass/PTFE fabrics with a hot air pistol is indeed possible, but is seldom done on account of the highly poisonous vapour given off by the welding process.

Joints in partial surfaces between fabric membranes are normally made by the fabricator in advance. If the area to be roofed over cannot be delivered in one piece, then assembly joints have to be provided in order to join the adjacent parts.

For the erection of the vehicle park roof at the Munich Waste Management Office, a high point structure, a conscious decision was made to use stiff clamping connections for the assembly joints between the partial areas. The prefabricated panels approx. 10 x 12 m in area of the 8.400 m² Glass/PTFE membrane were welded at the works in 70 m long strips and delivered to the construction site, where they were laid out and welded together. In order to be able to better compensate errors, the site weld seams were made with double width (right in Fig. 118).[1]

Fig. 118:
left: Repair work with a hot air pistol;
right: Welding of partial surfaces of Glass/PTFE membrane at the Munich Waste Management Office (AWM), Germany

1 *Göppert, K. (2003)*

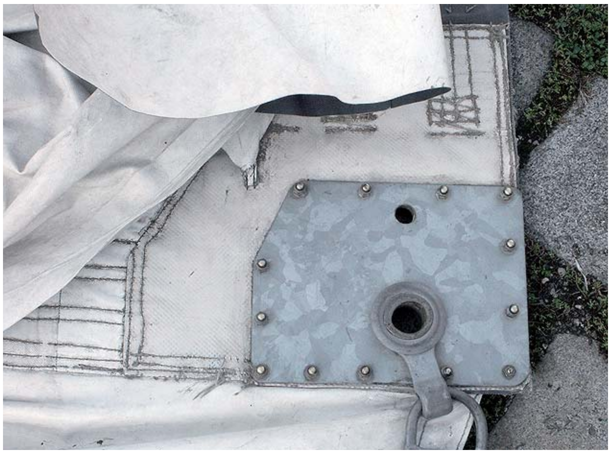


Fig. 119: *left:* PES/PVC fabric corners of a circus tent reinforced with sewn seams; *right:* Sewing the edge area of a Glass/PTFE fabric

2.5.1.2 Sewn seams

Sewn seams, which are the traditional means of joining fabric in tent building, make possible a direct connection of fabric thread to fabric thread to transfer force. In the construction of lightweight structures, however, sewn seams to join two sheets are rather the exception today, particularly as the perforation of the membrane by the sewing needle damages the waterproofing and has to be waterproofed later.

In highly exposed edge areas and corner cut-outs, sewn seams are still used today for connections, with the welded seams in these areas being additionally sewn (left in Fig. 119). When edge belts of Glass/PTFE fabric are used, these are also sewn to the fabric (right in Fig.119).

When sewing a seam, special care has to be taken of "tidiness". Excessive sewing speeds heat up the sewing needle strongly and burn holes in the fabric. Known forms of sewn seam are flat seam, turned-in seam and hem seam. The stitching types are lock stitch, zigzag and warp stitch. The best seam, but also the most expensive to produce, is the double turned-in seam, which has the two hems hooked over one another and is then sewn with many parallel lines of stitching. In order to provide weather protection and stop light passing through, the sewn seam can be welded over with a foil and sealed. This is normally done on the construction site by welding a prefabricated cover flap over the sewn seam.

2.5.1.3 Glued seams

Glued joints are only used in membrane construction today to join the seldom-used silicone-coated glass fibre fabrics. This type of fabric cannot be welded on account of its structure. Silicone is an elastomer, whose molecules are networked on a large scale, and elastomers cannot plasticize. If they are to be joined, then they have to be vulcanised similarly to rubber. The rubber elasticity is also preserved down to low temperatures.[1]

In order to be able to glue the part to be joined, the surface of the silicone coating must be treated. The solvent in the adhesive swells up the surface, the adhesion of the molecules is broken and a better adhesion is reached. Finally the adjacent pieces can be glued together with the networked adhesive. The strengths, which can be achieved with the correct parameters for the networking process, are comparable with the material strength.[2]

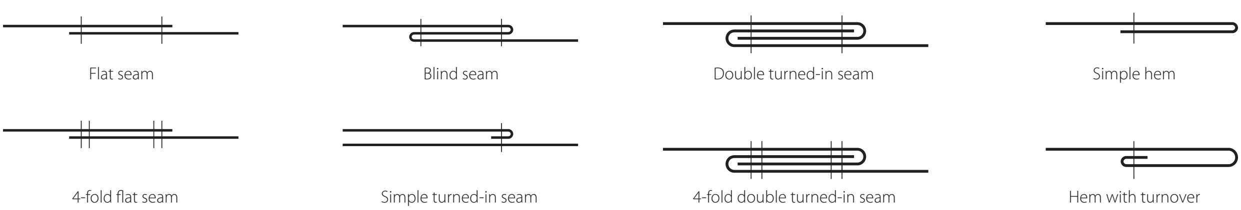
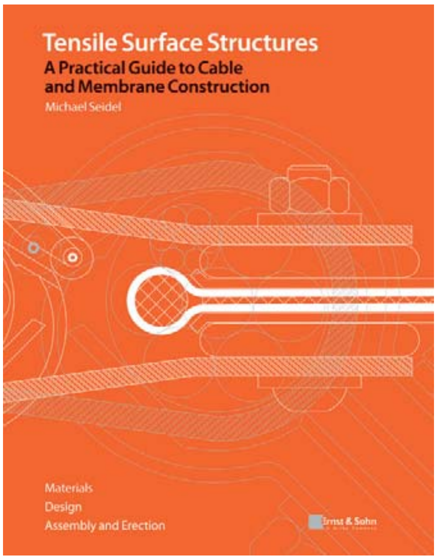


Fig. 120: Types of sewn seams

1 *DVS guideline 2225 (1991)*

2 *Blum, R. (2002-2)*

Book Recommendation



Seidel, M.

Tensile Surface Structures. A Practical Guide to Cable and Membrane Construction

Materials, Design, Assembly and Erection

Tensile surface structures are the visual expression of an intensive rethinking of the topic of building envelopes by designers. Advances in design methods, materials, construction elements and assembly and erection planning in the field of lightweight construction are enabling ever more exacting applications of tensile structures with envelope and structural functions, especially in roofing over large clear spans without internal support.
However, the particular mechanical characteristics of the materials used in the construction of textile structures demand consideration of the question of "buildability". This book provides answers by discussing the fundamental influence of material manufacture and assembly in deciding the most suitable type of building or structure and its detailing in the design process.
The fundamentals of material composition, manufacturing process, patterning and the behaviour of flexible structural systems are all explained here, as well as their use as structural and connection elements, and special attention is given to the erection of wide-span lightweight structures. The erection equipment is described, as well as the lifting and tensioning process and the construction methods used to erect the characteristic types of tensile structures, illustrated with a selection of example projects.
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