COMMON PROBLEMS IN THE DESIGN AND CONSTRUCTION OF MEMBRANE STRUCTURES

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Summary. This paper presents and discusses common problems frequently encountered in the design and construction of membrane structures.

Most of these problems can be avoided by careful design and preparation, which would take into account intermediate assembly and erection conditions. The following points should be considered, by assuring that:

- Realistic load assumptions are made, if necessary, with supporting load tests
- Individual fields are not too large
- Pre-assembly damage and kinks are avoided
- Slippage from snow, if possible, is avoided

When parallel to design, manufacture and assembly, a construction supervisor is tasked with reviewing and supervising all the stages, major damage can be avoided.

1 Introduction

Membrane construction is an interesting field of activity, which is often unknown to the civil engineer.

Membrane structures fascinate by their interesting shape and their often prominent locations.

Following several, sometimes spectacular membrane failures, a certain degree of uncertainty has been experienced by structural designers and clients.

The following article is intended to describe the common causes of damage observed by the author who has been engaged to monitor and assure the quality of membranes and membrane systems.

The author has not undertaken any design work or conceptual planning works in membrane-related projects. Instead, involvement has always been restricted to managing and / or supervising such projects on site on behalf of the client. In addition, the author has gained further extensive knowledge and experience of this technology from dealing with inspection and maintenance issues related to completed construction projects.

Experience shows that the greatest problems lie with the implementation of the design (during manufacturing and assembly) which is often the cause of the ensuing damage (both before or after construction is complete). In order to be able to explain more clearly the problems associated with all the stages of construction, it is first necessary to explain the individual steps involved in the design, manufacture and final installation of a typical membrane project.

2 DEFINITION OF A MEMBRANE STRUCTURE

In the context of this article, a membrane structure is defined as a surface of a flexurally soft building material, doubly curved and pre-tensioned and only capable of functioning in tension.

2.1 How does a membrane project work?

Compared to traditional methods of construction such as reinforced concrete or steel construction, membrane design and final assembly can be highly complex, dealing with changing dynamic loads, sensitivity in the quality and performance of the manufactured fabric and final on-site installation.

To understand the differences compared with classical construction, it is helpful to describe the individual steps of a membrane project.

2.1.1 Concept design and development of membrane shape

The design of a membrane structure is relatively complex because the shape is the result of a form-finding process due to the inherent flexibility of the material. This form-finding is iterative, since the selection of the material, the boundary conditions and the chosen pre-tension always influences the form, repeatedly.

Due to the exclusive tensile characteristics of the material, care must be taken during the design of the membrane surface that the applied pre-stress must never be reversed into compression under the influence of external loads. Compressive stresses can lead to wrinkling and loss of the intended shape.

It is a particular characteristic of all membrane surfaces that their shape and loading condition are interdependent.

Therefore, the geometry depends upon the interacting forces - and vice versa.

The process of creating and defining a final membrane surface is now made by form-finding software, which has largely displaced the previously customary iterative, experimental methods.

2.1.2 Structural analysis

The basic definition of the shape is followed by defining critical loads and deformation conditions. Particular structural analysis includes a focus upon the localised failure of any one membrane field, as well as the influence on loading due to snow and the potential for ponding of water.

Once these loads have been determined, the actual sizing of the membrane material and the surface and edge details are then designed.

Within the scope of this article, a particular topic which will be mentioned relates to the safety concept of membrane design, based upon partial safety factors.

An attempt is made to detect and cover some of the (negative) properties of the membranes by means of certain partial safety factors. Typical partial safety coefficients measure the influence of the biaxial stresses, long-term effects, environmental and temperature influences, the membrane material itself and influences from the erection. In addition, there is then a global safety factor for global influences.

This usually results in total safety factor coefficients of 5 to 7. Whether and to what extent these apparent high safety factors are able to achieve an adequate safety of a membrane construction must be examined separately in each individual case.

2.1.3 Cutting patterns

The pre-tensioned, spatially curved membrane surface has to be cut out by the manufacturer from planar surface elements and then joined together in such a way that the desired three-dimensional shape is created subsequently through pre-stressing.

Influence on the cutting patterns and fabrication geometry is based not only on the width of the available material but also a minimization of the blending and questions relating to the assembly technology.

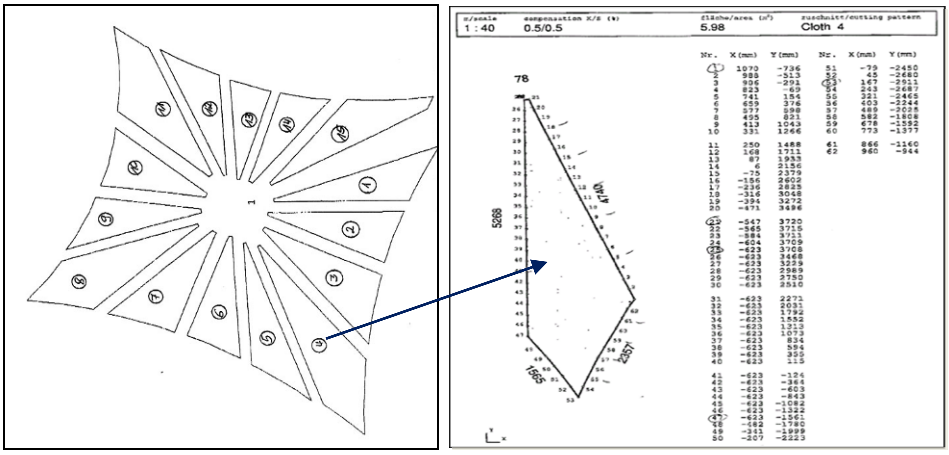

Figure 1 **Cutting patterns from overview to single pattern**

A particular difficulty for parties involved in supervision is that the design of the cutting patterns cannot be checked, unless undertaken by another independent designer. It is often not possible to determine whether the membrane has the desired shape under pre-tension (the more important would be an adjustable fastening of the membrane edges, see chapter 4.9).

2.1.4 Material selection

The choice of the most appropriate membrane material depends on many factors, such as:

- Strength,
- Durability,
- Cost effectiveness,
- Installation possibilities

A distinction is made between coated fabrics and single films.

Fabrics usually tend to be either Polyester-PVC or Glass-PTFE. For the most part, the types of films used are from transparent ETFE.

2.1.5 Determination of material characteristics, determination of compensation

Material characteristics, such as strength in the warp and weft direction, are initially specified by the manufacturer.

Within the scope of monitoring (see Section 2.1.6, approval in individual cases), this information is checked for each production batch.

Bi-axial stress-strain tests, partly influenced by temperature, are carried out on the cutting patterns and the relevant compensation required. These bi-axial tests provide important knowledge and guidance into the strain behaviour of the membrane under load as well as the time-dependent relaxation of the membrane.

If the compensating values, on which the cutting patterns are based, are not determined correctly, then the membrane will be either too small or too large, and subsequently cannot either be installed or has too little pre-stress and / or folds.

2.1.6 Approval in individual cases

In Germany construction projects using membranes are largely unregulated. The German Standard DIN EN 13782 is used for designing tensioned, membrane-type structures, including marquees and tents. In principle, in individual cases, it should be assumed in Germany that a building permit is required when choosing to build a membrane structure.

In order to monitor production, the accompanying material- and welded seam tests are usually prescribed. For this purpose, before the start of production and also during production, material samples and sampling of the most important details, are inspected and tested to destruction.

The author has experienced however, that in many cases, the quality of inspection and monitoring of the manufacture and final assembly of membranes is grossly inadequate. In the majority of cases, only one inspection of the manufacturing process and final installation is undertaken.

2.1.7 Assembling process in manufacture

During the assembling process, the membrane is cut from raw material and put together.

At the beginning of the material inspection (mostly sampled from a roll), a check is carried out on a light table in order to detect faults in the fabric or the coating and to consider these in the context of the cutting process.

This is followed by cutting of the membrane shapes, mostly on CAD-CAM controlled machines. Another possibility to draw stencils on plotters, cut them out, and then mark the sub-fields on the membrane material.

The joining of the individually-tailored shapes into a membrane field is usually carried out by means of welding. In the case of Polyester PVC this is by means of high frequency welding, or in the case of glass PTFE fabric by means of a welding beam. For Polyester PVC fabrics, details are welded with the application of a hot-air gun.

Depending on the material type, joints can also be sewn.

Figure 2 Welding of Polyester-PVC fabric with high frequency welding machine (Photo: CenoTec)

In addition, membrane details such as corners or reinforcements are manufactured; cable pockets are attached; and belts are sewn on.

After final visual- and dimensional inspections, the finished membrane bay is packed (see next chapter).

During the joining process, care must be taken that the material is treated with care. Especially for Glass PTFE fabrics wrinkles and kinks can occur and must be avoided at all cost.

2.1.8 Packaging / shipping

Especially with kink-sensitive Glass-PTFE membranes, sufficient attention must be paid to careful packaging. Irreversible damage to membrane fabrics and coating can occur as a result of improper packaging.

For the packaging of large membrane panels a considerable number of personnel is required. Close bending radii must be avoided or compensated for by using cardboard or foam rolls.


26 Feb 2003

Figure 3 Folding of a large membrane panel

The more carefully a membrane can be packed, the less chance there is of damage occurring.


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Bild 4 Folding of excess area at a large membrane panel, mind the foam rolls at photo on left, these are too small and do not prevent kinks when fabric is folded

The designers should, in any case, create a folding and packaging plan for the jointed sections and specify the minimum size of the folded packages.

2.1.9 Assembly

As a part of the installation preparation, auxiliary structures- and scaffolding are erected. The delivered membrane is unpacked and then spread either on the ground and lifted up as a whole or spread out at the appropriate installation height.

The membrane must then be connected to the substructure relatively quickly in order to be able to control the membrane in the event of wind.

This is followed by the application of pre-tensioning.

The tensioning of a membrane between fixed edges, in part, entails a great deal of effort for tensile stresses up to 5 kN/m.

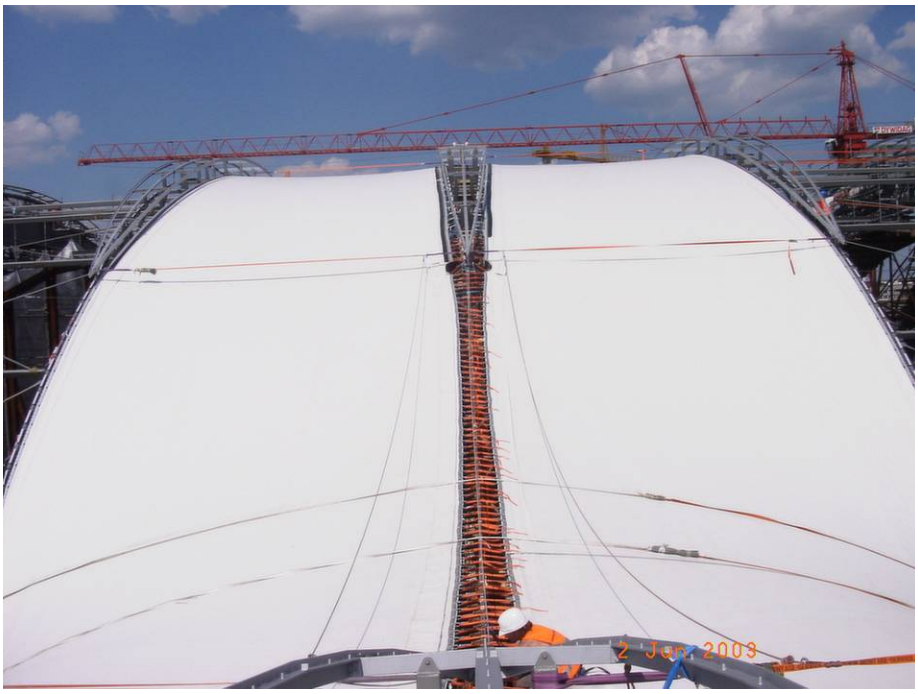

Figure 5 Battery of ratchet belts for tensioning oft wo adjacent membrane bays

In the case of adjustable high or low points, the stresses can be entered relatively easily, with appropriate design of the anchor points.

Figure 6 High point of a membrane panel during tensioning with hydraulics (© form-TL)

2.2 Typical detail solutions

There are many different solutions to join patterns to the surface or to attach to the edges of the membrane.

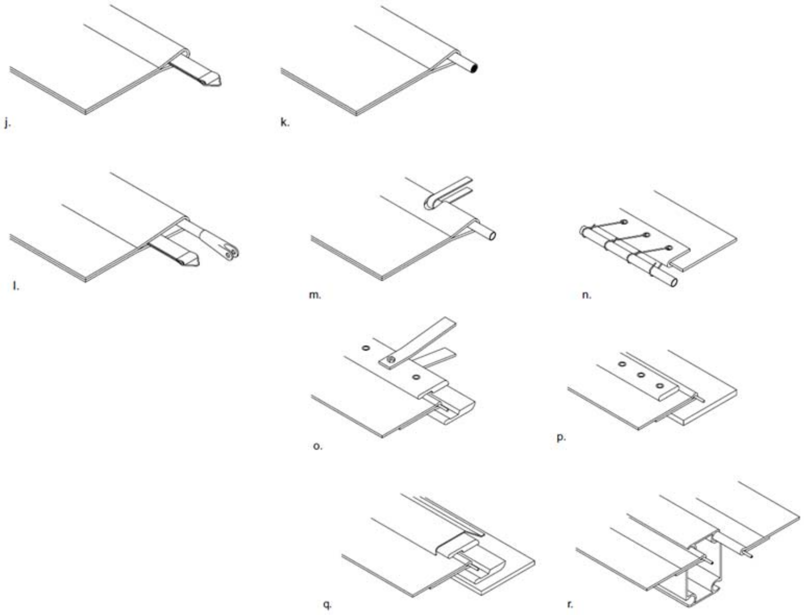

Figure 7 Schematic overview of edge details [2]

A comprehensive explanation of the many different detail solutions for edges, corner and area details would be beyond the scope of this article.

Figure 8 **Examples of good edge and corner details**

At this point, it should be pointed out that it is generally advantageous if the fastening of the membrane is carried out adjustable on rigid edges so that, if necessary, it can be adjusted.

This allows the pre-tensioning in the membrane to be adjusted so that stress reductions from relaxation can be compensated for. Therefore, in the case of adjustable edge fixtures, the original pre-tension in the membrane can be lower, as long-term effects can be compensated for.

In the following, four typical and frequently occurring detailed solutions are described.

2.2.1 Clamping edge

At the clamping edge of the membrane a keder stripe, welded to the edge of the fabric, is bolted between clamping plates. One of the two clamping plates is thereby wider than the others and can then be secured to the substructure.

Figure 9 Clamping edge, bolted to concrete structure (© Birdair)

This solution has the advantage that the tensioning tools are fixed to the wider clamp plate for pre-tensioning and not directly to the membrane via auxiliary clamps. A worse version of the clamping edge is described in chapter 4.7.1.

2.2.2 Keder profile

By using a keder profile, the membrane is threaded into a keder profile, which in cross-section is a three-quarters-rounded track, usually manufactured from aluminium, using the same principal adopted for feeding sails onto the mast of a sailing boat.

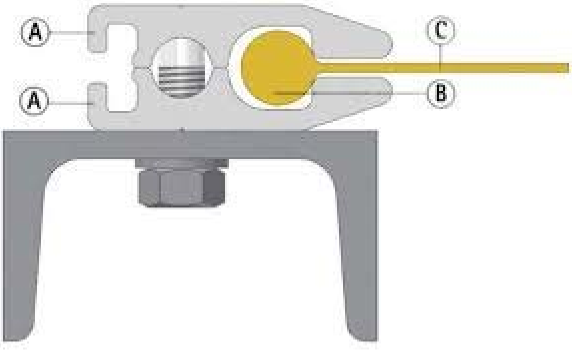

Figure 10 Cross section keder profile

The advantage of using keder profiles is that first the membrane can be spread out and the profile can be subsequently pushed on (see next photo).

Figure 11 **Keder profile is pushed onto the edge of an ETFE foil**

2.2.3 Rope edge

When connecting the membrane to an edge cable, there are basically two possibilities.

In the case of the cable pocket, the membrane is laid over and an edge pocket is created. In the edge pocket there is a rope or cable which is connected to the substructure.

There is also the possibility to allow the cable to run next to the membrane edge and to connect the membrane to the cable with clamping bars and straps.

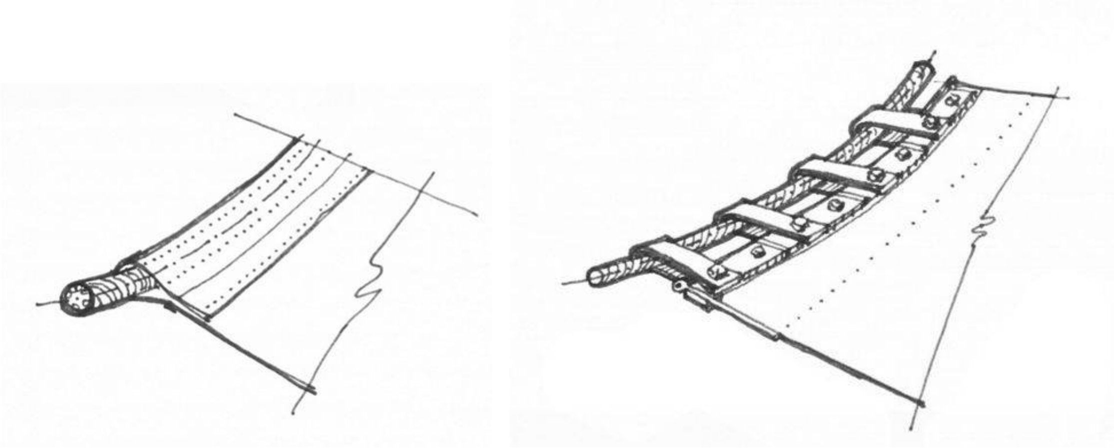

Figure 12 **Cable pocket (LHS) und cable edge with clamping bars and straps (RHS)**

2.2.4 Support arches

Membrane support arches are a relatively simple concept in order to create saddle surfaces, especially when installed on cable nets.

The membrane arches are frequently equipped with keder profiles on the upper side. A keder stripe at the underside of the membrane is then threaded into these profiles. This keder stripe has two tasks. It prevents the membrane from being lifted off the arch and, at the same time prevents the movement of the pivoted.

Figure 13 Membrane arches prepared for lift of membrane

For some projects, e.g. In the case of the fixed roof of the BC Place stadium (see figure 16), the membrane is exposed freely on the arches. The arches are coupled to one another by a cable extending in the longitudinal direction under the apex angles of the arches and are secured to prevent deflection.

3 INSTALLATION

The individual working steps of a membrane project have already been described in Chapter 2.

The actual installation procedure of the membrane is often neglected during design, however, particularly in the case of complex and large membranes, this places great demands on the personnel undertaking the work. Therefore, for this, the most important working steps are described in detail below.

When assembling a membrane, it is important to ensure that this is done, especially with glass PTFE fabrics, only at permissible temperatures and without damage and kinks.

3.1 Spreading out the Membrane

The process of spreading out the delivered membrane is not easy on the construction site in wind and rain. Usually, the package is placed on a scaffold table or belt net and spread there, usually with the help of a crane.

In the case of large panels, the membrane is often pulled over auxiliary belts and guided laterally. Care must be taken to ensure that under no circumstances shall any kinks be allowed to develop.

It is preferable if the membrane is delivered in a rolled form, and can be unrolled subsequently using a crane. However, this is only possible with modestly curved surfaces.

Figure 14 Unrolling of membrane with use of crane traverse (Photo: Montageservice LB)

During the spreading of the membrane, a temporary position must be securable at any time.

3.2 Connection to the sub-construction

After spreading and temporarily securing the membrane, it is connected to the substructure.

Keder profiles are slipped, clamping plates are screwed on, or edge cables are pulled into their pockets.

Often auxiliary structures are necessary for the introduction of the tensile forces. In some cases, auxiliary keder stripes (stripes welded on in the factory, which are later cut off) are of considerable assistance in installation.

3.3 Applying the pre-tension

In the case of a membrane with high or low points, the introduction of the pre-tensioning is usually simple: first the membrane edges are connected and then the high or low point is pushed or pulled.

At any rigid edge location, the membrane must be pulled continuously along its entire length. This means that in most cases numerous ratchet belts or threaded rods are used. During the installation design process, specifications for the forces are established, including rest periods required during tensioning.

The application of the pre-tension should be monitored with appropriate measurement device (e.g., load cells) so as not to exceed the scheduled pre-tensioning at any time.

4 COMMOM CAUSES OF DAMAGE

There are a variety of different causes for possible damage to a membrane structure. Usually, a single circumstance is not the cause of damage, but a combination of different factors.

According to the author's experience, the defects listed below are relatively frequent causes of damage.

4.1 Unrealistic load assumptions

In complex shapes or roof surfaces, it is often difficult to make realistic load assumptions.

It is important to ensure that loads from wind, snow and ice are correctly understood and that the design prevents the formation of water ponding. See also the Dresden Central Station, chapter 5.2.

The dynamic effects of slipping snow are extremely difficult to take into account. In addition, there is the fact that the snow is often lumpy and compact and an ice layer can form under the snow. This prevents realistic assumption of the actual loads, therefore is almost impossible. If possible, the elimination of the risk of snow slippage should be considered and designed out of the final solution.

4.2 Unconsidered constraints or load peaks

Possible constraints or load peaks are a sub-topic of the load assumptions. However, since a membrane is very sensitive to the introduction of local loads, this point should be considered separately.

Any hindrance to the free deformation of the membrane must be avoided or taken into account as a specific load case. If a peak load can occur, corresponding reinforcement must be provided.

Disregarding deformations and the resulting contact with other components can lead to partially large load peaks. At the Metronom Theatre in Oberhausen, on the rigging level in the interior of the theatre, a steel construction was installed retrospectively, which was physically quite close to the inner membrane. During heavy winds, the inner membrane was subsequently pressed against the sharp edges of the steel construction and tore along a length of about 20 metres.

4.3 Very large membrane fields

Very large membrane fields (individual sizes of more than 500 m²) lead to problems in several respects.

The handling of the membrane in the joining process is only possible by using a considerable number of personnel and by using cranes. The larger the membrane, the more likely folds are kinked or stepped upon - with the inevitable consequence of damage.

The given packing dimension (i.e. container dimensions, air transport) may not permit the necessary bending radiuses to be sustained or maintained

The membrane, which has a light surface, develops a considerable weight in several layers, which then causes the folds to become damaging creases or kinks.

During installation, large individual surfaces are difficult to handle and, above all, they cannot be secured temporarily.

In the case of more extensive damage, correspondingly larger sub-panels must be replaced.

Therefore, oversized membrane fields should be avoided. Large areas can be subdivided into individual membrane fields and these can then be connected with clamps or two-sided keder profiles.

4.4 Inadequate packaging

The temptation to convert a membrane panel, which is sometimes hundreds of square metres in size, into a transport package that is as small as possible, while at the same time minimizing the minimum bending radii of the material, is relatively high.

The pressure to meet agreed deadlines, and the intention to ship the membrane by air transport, often leads to inadequate packing being used.

The following photo shows a two-layer Glass-PTFE membrane of approx. 800 m² total area after opening of the transport crate. It is evident from the snow rests at the edge of the photograph that temperatures around the freezing point appear to prevail. This membrane thus transported and installed at sub-zero temperatures failed completely nine months after installation from snow load.

Figure 15 Glas-PTFE Membrane (approx. 800 m^2) packed particularly small

4.5 Folds and kinks

Folds and kinks, especially with Glas-PTFE membranes, lead to a reduction in the load-bearing capacity of the fabric.

Folds and kinks can be developed at several points during the production process, the packaging process and, of course, during installation.

In the case of Glas-PTFE membranes, kinks must always be avoided. According to the author's experience, instructions on this alone are not sufficient, therefore instead the individual work steps should be monitored.

4.6 Unfavourable installation conditions

Unfavourable assembly conditions can have many causes and characteristics. One example being the existence of quite a high height combined with limited accessibility for installation.

In addition, unfavourable conditions during membrane assembly can arise from time pressure, wind and low temperatures.

Substantially greater time pressure can lead to unsatisfactory handling or care of the membrane, including lack of regard for the necessary relaxation of the membrane during the tensioning process.

Time pressure also means that often the requirement for a favourable weather window is ignored. If strong winds occur during an (unsecured) assembly condition, damage is almost certainly pre-programmed. An example of this is the façade of the Cape Town Stadium (see chapter 5.3).

Glass-PTFE membranes cannot be installed at low temperatures. The temperature limit is discussed repeatedly, but it is essential that a minimum temperature of +5°C is observed at all cost.

A further repeated discussion is to ensure that the membrane is heated, preferably whilst contained inside the transport box, in order to avoid damage to the fabric by transport movement at low temperatures. The approach is not incorrect, however, it must be noted that the membrane will subsequently assume the ambient temperature once again immediately after it has been spread out.

4.7 Difficult to install details

The conditions and requirements of the subsequent installation must be taken into consideration as early as the design stage. Potentially cost-effective or easy-to-maintain details may be difficult to mount on the construction site, possibly at high cost or leading to damage of the membrane.

Two examples will illustrate this.

4.7.1 Clamping edge

The very simple clamping edge of the membrane, at which the membrane is fixed with a keder stripe by means of threaded bolts and a clamping bar, can hardly be installed if there are no adjustment possibilities on the edges. This detail can only be mounted free of stress, for example, when a high-point membrane is used.

Figure 16 **Clamping edge, planned details on RHS, LHS shows situation during installation with auxiliary clamps**

A substantially better clamping edge is that which uses two clamping profiles from which the wider one can be secured to the sub-construction (see Chapter 2.2.1)

4.7.2 Keder profile on membrane arches

The membrane arches described in Chapter 2.2.4 with the keder profile, into which a keder stripe on the underside of the membrane must be threaded, considerably complicate the installation of the membrane. Not only must the arches be corrected in their lateral inclination, as the membrane is pulled over, it is also necessary for the installation team on the underside of the membrane to monitor and ensure correct threading of the keder stripe onto the membrane arch.

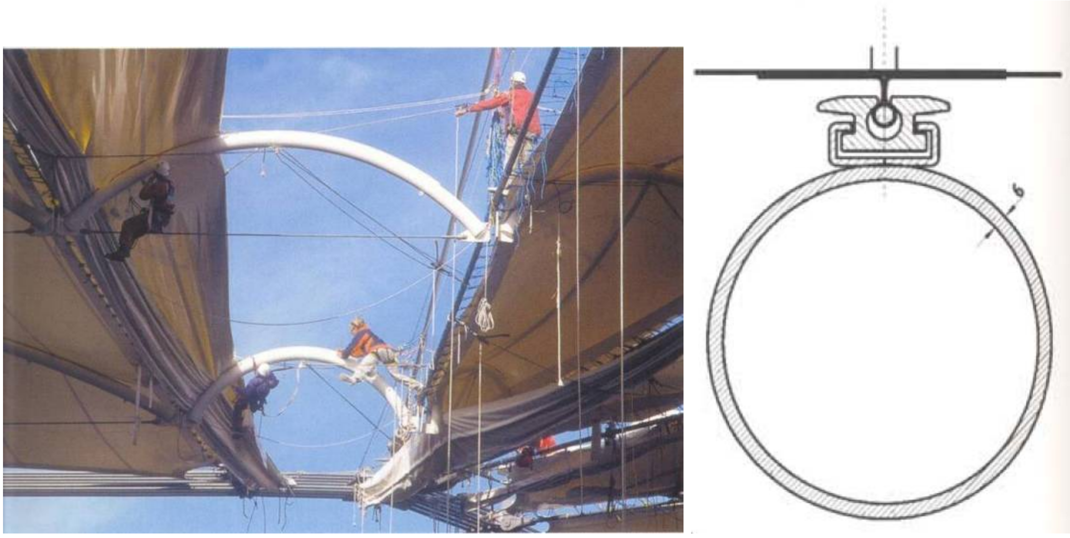

Figure 17 **Membrane arches with membrane pulled over, mind the workers hanging under the arches (LHS), Detail of arch with keder profile (RHS)**

It would be better if a keder profile could be pushed onto the keder stripe on the underside of the membrane after assembly and then connected to the membrane arch.

It would also be conceivable to screw a clamping bar from above through the membrane into a corresponding profile on the arch.

4.8 Missing installation aids

The author can confirm that on several construction sites only the final installed condition of the membrane edge details were considered, instead of planning the actual sequence of installation steps which resulted in this final condition.

The following photo shows a battery of small tirfers, which have been hooked to the underside of a metal flashing. There was simply no other method to initiate the necessary pre-tensioning forces at the edge of the membrane since no assisting installation device or methodology was planned at design stage.

Figure 18 Battery of tirfers to tension a membrane bay

The following photo shows another example, the tensioning process of a single-ply ETFE film. Although the pre-tensioning forces are rather small here, the assembly team had to build an expensive (and not altogether trustworthy) tensioning device in order to ensure that the tensioning in the foil was achieved.

Figure 19 Tensioning of a single layer ETFE-foil

This lack of installation assistance leads to the installation being made more difficult and attention is no longer paid to ensure any necessary and careful treatment of the membrane.

Unfavourable installation conditions also lead to the pre-stressing forces being applied too quickly in the membrane in order to be able to complete the installation as quickly as possible.

4.9 Non-adjustable edges

Attaching the membrane to the substructure with clamping edges without properly designed adjusters causes two major problems.

If the attachment of the membrane to the rigid edges is adjustable, long-term effects, such as creep and relaxation, which lead to reduced tension in the membrane, can be compensated for. In this instance, the applied pre-stress to the membrane can be lower because re-tensioning would then be possible. Without an adjustable clamping edge, considerable pre-stresses must be introduced, with the associated extra effort required during assembly. In addition, the membrane must then be tensioned over a longer period of time until the material has reached the desired geometry without the need for excessive forces. These extended periods of time have a corresponding influence on the cost of resources required (i.e. personnel, equipment and materials).

A second, negative aspect of the fixed, non-adjustable clamping edge relate to the ensuing tolerances in the substructure to which is connected. Deviations from the intended geometry then influence the membrane directly, which can lead to considerable damage. The following photo shows a membrane which has been connected to a steel substructure with clamping plates. Dimensional deviations in steel construction lead to an offset between adjacent clamping plates, to shear forces in the membrane edge and ultimately to a tearing of the membrane through the clamping edge.

Figure 20 Offset of clamping plates fixed to steel structure

5 DAMAGED MEMBRANES - EXAMPLES

The following is a description of the damage known to the author. The selection of these examples of damage is not entirely arbitrary, instead they demonstrate common causes of damage.

5.1 Veltins-Arena Gelsenkirchen

At the Veltins Arena in Gelsenkirchen in the winter months of 2010/11, damage to 7 of the 40 roof fields occurred within three days. The roofs were largely irreparably damaged. Fortunately no one was injured.

Figure 21 Aerial view of Veltins-Arena, end of December 2010

Figure 22 Veltins-Arena, snow loads on the stand after failure of a roof panel

After extensive investigations and structural calculations, the following causes of damage were determined:

5.1.1 Unrecognized localised point loads

The membrane was secured by means of suction cables on the upper side against lifting loads under wind suction. These cables were tensioned downwards by short cables through the membrane roof panels, in three locations.

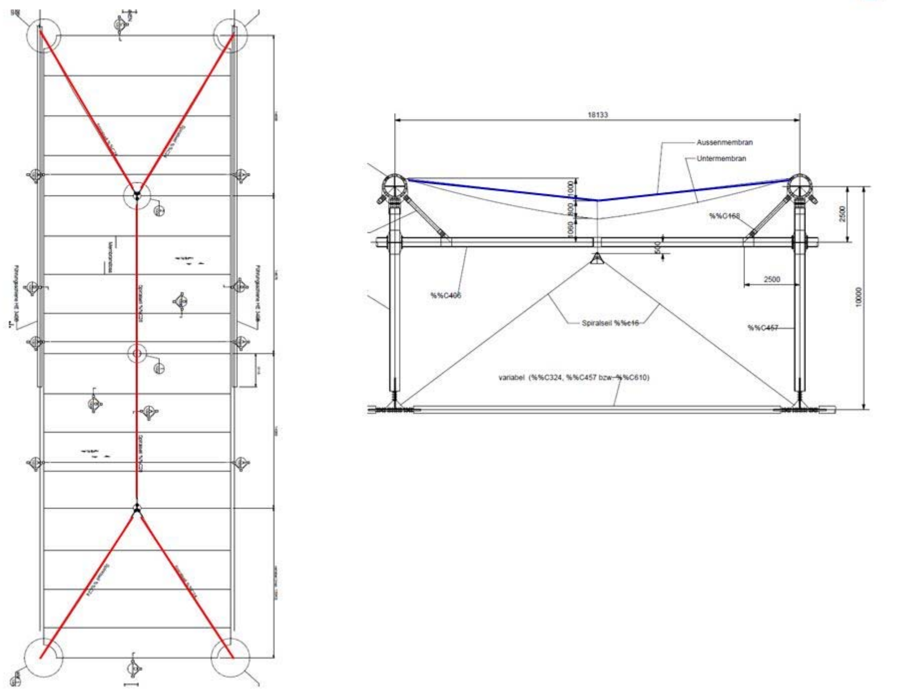

Figure 23 **Veltins-Arena, view onto a roof panel with suction cables (red), cross section with outer membrane (blue)**

During structural analysis of the membrane, the membrane was assumed to be a rectangular field with clamping at the edges. In the case of downwards acting loads, especially in the event of snow loads, the suction cables on the membrane were not considered.

In fact, the suction cables were connected to the membrane by means of a clamping plate at the three points at which they were tensioned downwards. As the membrane experienced snow loading in the winter of 2010/11, the membrane deformed according to design analysis, but snagged unintentionally on the clamping plates. Since these points had not been considered, the membrane was not reinforced at these clamping points, which caused the membrane to tear in these locations.

5.1.2 Load bearing capacity of the membrane reduced

During investigation into the damaged membrane fields, it was found that the tear resistance of the membrane fabric, compared to its original tear resistance during installation, had reduced significantly.

In addition, pre-damage to the membrane could be confirmed by the observation of kinks which had arisen during assembly and / or during installation.

Both factors led to a reduction in the load-bearing capacity of the membrane.

5.1.3 Dynamic effects caused by slipping snow

Regarding the various identified damage, which occurred in part only a few hours after each other, the effect of snow on the roof areas was varied. On some fields, the snow lay more or less evenly distributed over the entire roof surface compared to the field which failed. Here, the above-described load peaks at the unintended suspension points may have been decisive in defining the cause of the damage.

In other fields the snow had slipped down to the gutter. Dynamic effects, culminating in the fact that the compacted snow mass, which slipped with increasing speed, strongly deformed the membrane at the lower connection to the steel structure and probably also pressed against the steel structure. As a result, local load peaks occurred, which led to initial tears.

5.1.4 Build-up of ice under snow on the roof

The effects described above, during which time the snow had slipped off the membrane, were aggravated by the fact that under the snow layer a several centimetres thick ice layer had formed on the membrane. As a result, this ice had acted as a knife during the slipping process, thus slicing through the membrane material.

The ice forms under the snow layer, when the snow heats up from underneath, i.e. from the interior of the stadium, and freezes again once temperatures drop. In addition, rainwater is able to seep through the snow layer, and can subsequently freeze at the boundary layer to the membrane.

Conclusion: Peak loads were not identified and the membrane material had been pre-damaged by kinks. The membrane was locally damaged by the dynamic effects of unhindered slipping snow, together with the formation of ice below.

5.2 Main railway station, Dresden

At the membrane roof of Dresden's main railway station, which was built between 2001 and 2006, 5 to 14 m wide fields of Glas-PTFE fabric are stretched between a secondary structure on the historical framework arches. For every second axis, the membrane forms a funnel for dewatering the roof surface.

Figure 24 Main station Dresden, partial view of roof with funnels

In the winter of 2009/2010 a large tear occurred at one of the funnels. The membrane was cut at a height of about 3 m, permitting a lens-shaped opening to be observed. Inside the funnel lay a compact lump of ice and snow to a height estimated to be 2.0m.

Figure 25 Main station Dresden, ruptured funnel with snow filling

At first, it was assumed that this was a singular event due to damage to the funnel membrane. In the winter of 2010/11, however, a further eight funnels with a similar damage pattern tore.

Figure 26 Main station Dresden, ruptured funnel with snow filling

In the structural calculation of the membrane roof, snow loads on the basis of a wind and snow load report were taken into account. Local snow accumulations and filling of funnels with snow were also considered.

The actual snow in the funnels, however, was heavily compressed and had developed a density almost the same as ice. Moreover, the surface of the clumped snow was not smooth, but partly exhibited fist-sized depth between peaks and troughs.

Figure 27 Main station Dresden, clumped snow in funnel with local peaks

The cause of the damage lay in an overloading of the membrane by the formation of snow and an ice wedge in the funnel. Due to this wedge, very high stresses occurred locally in the membrane, which finally led to the failure of the material.

It could be proven that in the wind and snow report as well as in the structural analysis of the membrane, a sufficiently high snow weight was calculated.

However, it was clear that in the case of the local observations, that is to say in the funnels themselves, inadequate high snow loads or ice loads were assumed in the structural analysis of the membrane, therefore were inadequate to cover the prevailing conditions at the time, including the slippage of snow.

The resulting combination of snowfall, low temperatures over an extended period of time and a subsequent rainy season caused unfavourable conditions for the load on the hoppers. It is extremely difficult to calculate or assess the dynamic effects of slipping snow, especially when assessing large quantities (of it).

Conclusion: The load assumptions adopted in the area of the funnel were totally inadequate for the eventual prevailing load conditions. Additionally, the dynamic effects from slipping snow were not considered.

5.3 Green Point Stadium, Cape Town, South Africa

The assembly of the façade at the Greenpoint Stadium in Cape Town had to be carried out at the end of a tight program, therefore there was extreme time pressure to complete this.

Although several fields were already assembled and a degree of expertise should have been gained as a result, wind forecasts were ignored under the prevailing time pressure.

Strong wind during the installation of a façade field led to the destruction of the Glass-PTFE mesh fabric, since the high forces developed during assembly could at times only be transferred at certain individual points.

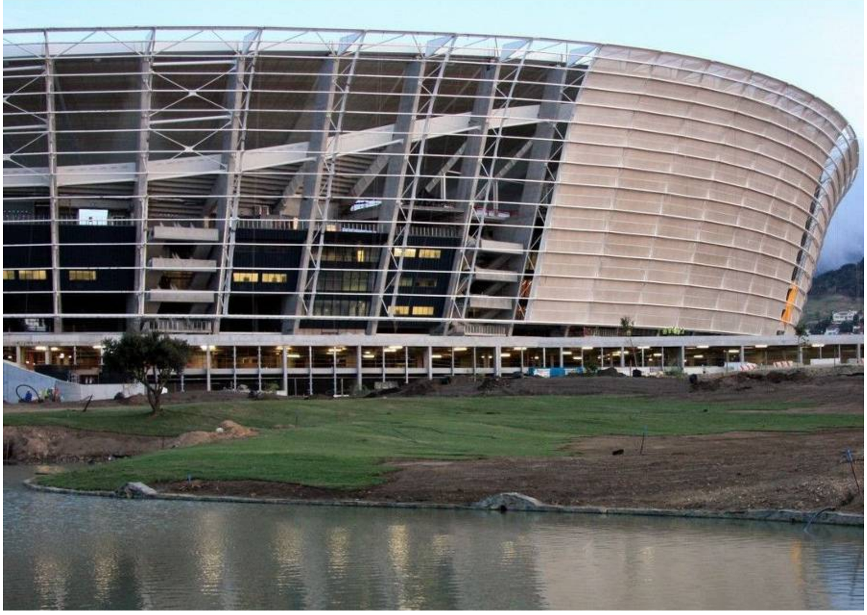

Figure 28 Green Point Stadium, facade during installation

Figure 29 Green Point Stadium, wind damage to facade panel

Conclusion: It was installed under unfavourable weather conditions so that strong wind could damage the membrane during intermediate assembly conditions. The loss of time due to the loss of the façade field was, of course, significantly higher than the waiting time which should have been taken in order to ensure optimum installation conditions.

5.4 Velodrome, Abuja, Nigeria

The Velodrome in Abuja, the capital of Nigeria, was built in 2003 and used for the All-African Games, together with the adjacent National Stadium.

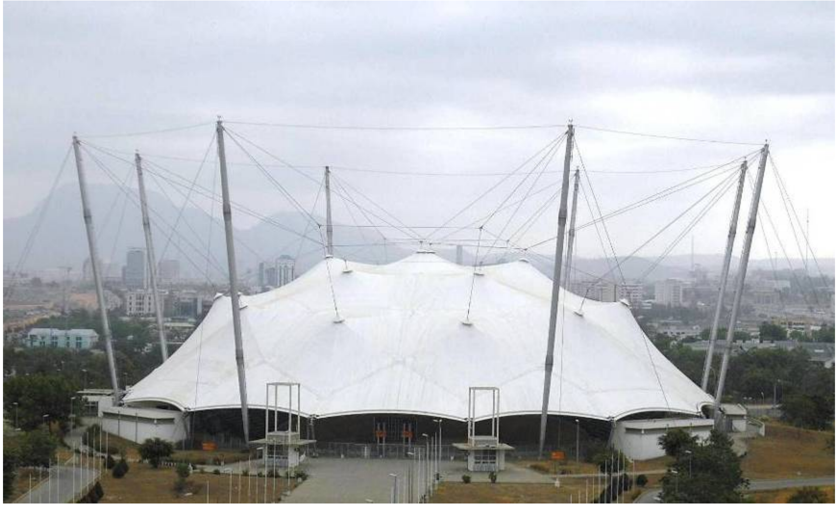

Figure 30 **Velodrome Abuja, Nigeria**

On the last day of the All-African Games the membrane roof was almost completely destroyed during a thunderstorm.

Figure 31 **Velodrome Abuja, Membrane damaged after thunder storm**
© Getty Images

As is often the case, the cause of damage has several sources.

The original design anticipated that the membrane of the entire dome should be assembled on the ground and then suspended from a rope net.

This led to extremely large membrane fields being created, which had to be spread and assembled on the ground. Due to the significant 3-dimensional curvature of the roof, the membrane laid on the floor had a great many folds. Due to a lack of supervision, the assembly team was permitted to walk over these folds, leading to initially unobservable kinks being created in the material.

With the aid of structural calculation, the deformations of the roof under wind influence were investigated. Above all, the catwalk suspended under the membrane on the rope net had to be able to absorb the deformations. However, a critical point was not taken into account when considering membrane deformations, namely access to the catwalk. At a particular point, a ladder is connected to the catwalk from the ground. This location formed a fixed position within the catwalk, at which point deformations were restricted.

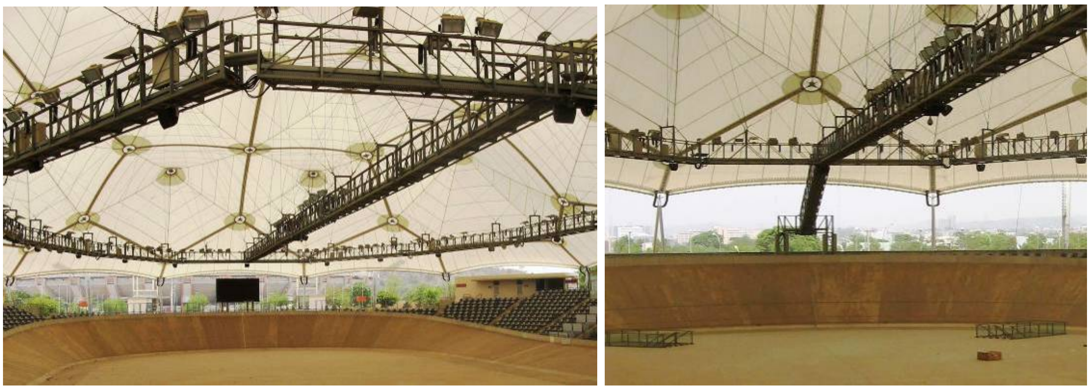

Figure 32 **Velodrome Abuja, catwalk under the roof, photo RHS shows access from ground level to catwalk**

During a strong thunderstorm with high wind loads and corresponding deformations of the roof, the membrane was pressed against the railing of the catwalk at the fixed point and tore. As a result of the above-described damage (kinks) during assembly, the initial tear propagated further and ultimately led to the complete destruction of the membrane.

Conclusion: Constraints had not been considered, the membrane fields were too large for appropriate assembly, and assembly had not been monitored, resulting in membrane material being kinked and damaged.

6 SUMMARY

This paper has discussed and clarified the frequent problems relating to the design, manufacture and installation of membrane structures, including offering solutions to avoid expensive damage.

The main and most frequent causes of problems with the construction of membrane structures and subsequent damage are:

- Unrealistic assumption of loads, especially with regard to snow loads and dynamic effects from slipping snow
- Lack of foresight of possible peak loadings
- Oversized membrane fields and thus also inadequate packing requirements
- Folds and wrinkles
- Unfavourable installation conditions
- Installation-unfriendly details and missing installation aids
- Absence of adjustment possibilities

Most of these problems can be avoided by careful design, which should also take account of the intermediate and final installation conditions. The following points should be observed:

- Adopt realistic load assumptions, if necessary, with tests and/or mock ups
- Do not select individual fields to be too large, observe packing requirements, and take into account installation options
- Monitor the manufacture and installation sufficiently in order to ensure quality and to avoid damage or kinks

Slipping of snow should be prevented wherever possible. If a membrane surface is designed for snow loads, this should be in a manner to permit the snow to remain on the roof surface and to thaw gradually. If slipping of snow cannot be prevented, the membrane edges should be designed so as to offer as little resistance as possible to the sliding snow.

In Germany, the membrane material itself as well as the surface and edge details are tested thoroughly in all membrane projects. However, due to a lack of published guidance for use at the design stage, attention to monitoring the various processes of membrane construction, right through from initial concept design to production and installation, is inadequate.

The obvious conclusion is that if a dedicated person were to be appointed to supervise all aspects of the design, factory manufacture and installation on site, this appointment would go a long way to ensuring that significant damage to membrane structures is avoided.

7 REFERENCES

[1] Bauen mit Membranen DETAIL Zeitschrift für Architektur, Heft 6, 2000.

[2] Koch, Klaus-Michael; Habermann, Karl J.: Membrane Structures: The Fifth Building Material, Prestel Verlag, 2004.

[3] Seidel, M.: Textile Hüllen, Bauen mit biegeweichen Tragelementen, Ernst & Sohn, Berlin, 2008.