architectural membrane association

Design aspects of single-layer ETFE film systems (compared to pneumatic cushions)

Karsten Moritz, 2021, January 15th

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1 Types of construction with ETFE-films

Due to their pre-stress the membranes used in the architecture are divided into two types of construction, pneumatically and mechanically pre-stressed constructions. Both types differ in their appearance and in their load carrying behavior. Therefore, their safety concepts could also be different.

The distinction between pneumatic and mechanically pre-stressed systems applies equally to technical textiles and films (foils).

This document only refers to the single-layer (mechanically pre-tensioned) structures made of ETFE-films, or to their differences to the pneumatic structures. The question arises as to whether both types of construction require different safety elements for the structural design. To do this, one has to know where the static-constructive differences are.

According to the semi-probabilistic safety concept of the Eurocode, the differences are to be found in the following two categories:

- differences on the action side
- differences on the resistance side

According to the principles of structural design (EN 1990), the resistance side contains the component's response to the respective action. This answer on the resistance side can be material-related or system-related.

2 Impact side

The impact side contains the actions to be applied and the action combinations. The decisive influences for both types of construction are as follows:

- dead weight
- pre-stress
- wind loads (quasi- static, dynamic)
- snow loads
- water loads (water pond)
- temperature
- …

In addition to the basics of the structural design (EN 1990), the Eurocode already provides the specifications for the loads and load combinations to be applied, taking into account the regulations on density, dead weight, wind loads and snow loads (see series of standards EN 1990 and EN 1991).

In this regard, the single-layer (mechanically pre-tensioned) ETFE film systems do not need to be considered separately. The aerodynamic shape coefficients (cp) are of course dependent on the respective system geometry and must therefore be determined on a project-specific basis. The rules for this are already defined in EN 1991-1.

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In the following, the focus is on the three other effects:

- pre-stress
- water loads (water pond)
- temperature

The question arises as to whether these three effects must be regulated differently in the intended Eurocode for single-layer (mechanically pre-tensioned) constructions (made of ETFE-film) than for pneumatic structures.

2.1 Pre-stress

The pre-stress must not be chosen too low so that...

- the film is in a state of tensile stress in all load cases and is therefore free of folds
- deformations of the membrane system are limited
- susceptibility to wind-induced vibrations are minimized (dynamic excitation with the risk of material fatigue must be excluded).

However, the pre-stress must not be too high so that the film ...

- does not creep (pneumatically pre-stressed systems)
- does not relax (mechanically pre-stressed systems)
- does not make assembly unnecessarily difficult or impossible.

2.1.1 What happens if the pre-stress is too low?

If the pre-stress has been chosen too low, larger deformations under load must be expected, of course.

There is also the risk of susceptibility to vibrations as a result of wind excitation. Individual cases are known in which ECTFE and ETFE-films were destroyed by wind-induced vibrations. This applies to airless or insufficiently filled pneumatic structures as well as to single-layer (mechanically pre-tensioned) films. If the tension-free or low-tensioned membrane flutters in the wind, cyclical (high-frequency) bending stress occurs and the film may fail very quickly due to permanent bending stress and embrittlement. At the end, the picture of the break of the film is clear, it breaks like glass.

ETFE-films are often installed in combination with stainless steel ropes or cables to increase the span. With these constructions, the focus should not only be on adequate film pre-stressing, but also on sufficient pre-stressing of the ropes and on limiting the rope length between the supports.

As the rope length increases, the required rope pre-stress increases disproportionately. With sufficient pre-stressing in the film and in the rope as deformation limits for the film, rope and primary structure, the risk of the failure type mentioned can be excluded.

If the pre-stress of single layer ETFE-systems is too low, there is also a risk that the film gets wrinkles, especially at high temperatures. This is basically a serviceabilty problem. However, due to large deformations under snow loads, the risk of water ponds increase, especially by heavy rainfall at high

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temperatures (depending on the climatic environment). Then, a water pond can lead to an ultimate limit state (ULS).

Conclusion of the above

For the reasons mentioned above, it is essential to define a lower limit value for the pre-stress. This applies to pneumatic structures and to mechanically pre-stressed systems, too.

2.1.2 What happens if the pre-stress is too high?

A pre-stress which is too high complicates and lengthens the assembly. It increases the risk of damage from irreversible residual strains (plastic deformations) or tears in the areas nearby the tensioning-tools and in the corners, especially at cold temperatures. This should be avoided, therefore.

Furthermore, a pre-stress which is too high does not limit the deformations of the film and also does not offer increased safety against a loss of the pre-stress in the film at the end - for the following reason:

Retardation (creep) is understood here as the slow change in geometry (elongation) under permanent load. The load can be variable or constant. In the case of pneumatic structures, creep processes, for example caused by too high pre-stress (e.g. too high internal pressure), mean an increase in the sag that can be excluded with an upper limit value for the pre-stress.

Relaxation, on the other hand, is understood to mean the slow decrease in pre-stress with a constant geometry of the edges (perimeter). Single-layer, mechanically pre-stressed systems do not creep, they relax if the pre-stress is chosen too high. This means that the tension in the film decreases over time until it reaches a state of equilibrium. This is inevitable, since a pre-stress that is too high is the cause of the relaxation. If the pre-stress decreases over time, there is no longer any reason for the film to relax any further.

The state of equilibrium is automatically established over time. It is described in the relevant literature on polymer materials as the creep or relaxation limit. For visco-elastic-plastic thermoplastics, this is around 50% of the yield stress. Linear elastic material behavior (Hooke) can be assumed up to the relaxation limit even for permanent loads.

With the first yield point (yield stress ~15 MPa at + 23 ° C) the creep and relaxation limit is approximately 7.5 MPa, therefore. The pre-stress should not exceed this value at 23° C. For a 250 µm thick film, this value corresponds to a pre-stressing force of approx. 1.8 kN/m. If one relates the value to the second kink at 21 MPa at 23° C (instead of the first one at 15 MPa) the result means an linear elastic range of 36% exploitable for the pre-stress.

The relaxation limit value can be determined with relaxation tests.

Creep tests would also be conditionally suitable for determining the relaxation limit if samples with different loads (e.g. 3, 6, 9 and 12 MPa) are relieved after a long-term exposure (e.g. 1000 h) and the residual strain is measured after a defined time. The relaxation limit can be estimated with the sample for which no residual strain can be measured. Film tension measurements should confirm the results of the laboratory tests.

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With ETFE foils, the relaxation is overlaid by a second positive process. It can be observed in practice that wrinkles in ETFE films disappear over time. Apparently, stress redistribution from high to low stress areas takes place in the film. The pre-stress is harmonized, obviously. Foil tension measurements should also prove this second process.

Conclusions of the above

For the reasons mentioned, it is essential to define also an upper limit value for the pre-stress in single-layer, mechanically pre-stressed systems. This is also recommended for pneumatic structures when increased sags due to a too high pre-stress are undesirable.

Increasing the pre-stress in single-layer systems to values above the relaxation limit is pointless, even harmful, since the film is unnecessarily stressed at the beginning and is also installed thinner than necessary due to its expansion. In addition, if the pre-stress is selected too high, it makes assembly more difficult and increases the risk of damage.

For the structural design of ETFE-film systems, the introduction of a pre-stressing range with upper and lower limits is to be introduced.

The limits for the pre-stress are temperature-dependent. With the help of k_{temp} values, the range from T = + 23 ° C can be converted to other temperatures.

In the case of mechanically pre-stressed systems, irreversible residual strains (plastic deformations) must be excluded. As shown, this cannot be prevented by increasing the pre-stress. They can only be excluded by limiting the maximal stresses resulting in the different load cases.

Therefore, a modification factor k_{perm} = 3.5 [-] ([1], [2]) applied on mechanically pre-tensioned ETFE-film systems as reduction factor on the strengths values in permanent load cases (pre-stress), would not be appropriate. It cannot prevent irreversible residual strains (plastic deformation) from occurring when the external loads are too high.

In addition, the k_{mod} factors describing the material should have identical values for both systems if the same material is used. Instead, the previously unused modification factor k_x [-] could be used as a factor for single-layer (mechanically pre-tensioned) systems, provided that irreversible residual strains (plastic deformation) are not excluded by the new design concept.

2.2 Influence of temperature

As known, the influence of temperature on the material behavior of plastic materials must be taken into account. All mechanical properties are affected. This applies, for example, to the following characteristic values

- stress (-)
- strain (+)
- stiffness(E, G) (-)
- tensile strength, yield stress and creep or relaxation stress (-)
- elongation at break, at yield and creep or relaxation elongation (+)
- deformation under load (+)

\+ increase when temperature rises

\- decrease when temperature rises

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Here, each load case (in the case of multi-layer pneumatic structures also each layer) temperature range (min / max) is assigned. As a rule, the maximum and not the minimum film temperature is decisive for the dimensioning in the respective load case. This is due to the fact that with increasing temperature, the reduction in limit values (e.g. tensile strength) has a greater impact on the verifications than the reduction in stiffness and the increase in deformation.

Deformations and temperature-related fluctuations in the pre-stress are of course not only dependent on the material and the temperature difference, but also on the system. This is why single-layer mechanically pre-stressed systems differ from pneumatic systems. While pneumatic ETFE-film structures only change their shape (increase in sag) when heated under constant overpressure that is too high, the geometry of the mechanically pre-stressed systems remains almost constant. This applies to both flat and anticlastic film systems with homogeneous pre-stress. When heated, the mechanically pre-stressed systems react by (reversible) relaxation, i.e. their pre-stressing decreases. As a consequence, the pre-stress increases reversibly as it cools down. This is where the substructure comes into the game: The pre-stressing in a single-layer (mechanically pre-tensioned) ETFE-film does not depend on the thermal expansion of the film or the thermal expansion of the sub-structure, but on the ratio of both. This is because ETFE-films and, for example, steel (substructure) have different coefficients of thermal expansion. Both components, film and substructure, can also have different temperatures. This is due, on the one hand, to the different heat absorption capacity of the components, and, on the other hand, to the fact that the substructure can be exposed to the indoor climate of a building, while the film represents the interface between the indoor and outdoor climate.

Conclusions of the above

The structural analyses, the temperature range of the film(s) in the respective load case must be taken into account, for both types of construction.

The relaxation limit is, like the yield stress, temperature-dependent. In case of single-layer, mechanically pre-stressed systems, it is therefore important to check whether the film still has residual pre-stress at a high design temperature and does not exceed the relaxation limit at a low design temperature. The following limits have proven to be reliable in practice (for temperatures selected):

nominal pre-stress at +23°C:	**4,0** MPa $\leq \mathbf{p_{+23°C}} \leq =$ **7,5** MPa
pre-stress limit at 0°C:	$\mathbf{p_{0°C}} \leq 7{,}5 / 0{,}9 =$ **8,3** MPa (Ansatz $k_{mod,\ t=-0°C} =$ 0,9 [-])
pre-stress limit at -20°C:	$\mathbf{p_{-20°C}} \leq 7{,}5 / 0{,}8 =$ **10,7** MPa (Ansatz $k_{mod,\ t=-20°C} =$ 0,7 [-])*
min. pre-stress limit at +50°C:	$\mathbf{p_{+50°C}} \geq$ **0,0** MPa

* It has not yet been clarified if a temperature-related exceedance of the stress limit by relaxation is reversible.

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2.3 Constructive influences

The pre-stress of the single-layer (mechanically pre-tensioned) ETFE film systems in the building is influenced by the following processes and their fluctuation range (tolerances):

- compensation
- cutting process
- welding process

2.3.1 Compensation

Experience shows that the different ETFE film products have different material properties. The stiffnesses (E, G) of AGC FLUON NJ are only about 80% of the stiffnesses of the product NOWOFLON ET6235Z from NOWOFOL. The compensation values should take this difference into account so that the nominal pre-stress can actually be achieved on the structure.

Since the compensation values are based on empirical values for the various products and the various geometries on the building and also take into account the following process-related influences, the standardization of compensation values would be endless.

2.3.2 Cutting process

The cutting (planning and execution of the cuts) defines the geometry of the partial surfaces that are later welded together.

Due to the different thermal expansion coefficients of the membrane material (here: ETFE) and the measuring tool (e.g. made of steel), cutting at different temperatures inevitably leads to different partial surface geometries and thus also to different pre-stresses. The cutting temperature in the production hall must therefore be documented and taken into account in the compensation if necessary.

For example, the compensation is corrected if the deviation is outside of a tolerance range, e.g. T = + 23°C (± 5°C).

2.3.3 Welding process

The geometry of the membrane element is influenced by the welding process. The most important influence of the welding process on the membrane geometry (and thus also on the pre-stress of single-layer systems) is the weld shrinkage. Depending on the process and material, this can significantly exceed the compensation values of ETFE and thus lead to an overstretched film if it is not taken into account. It is the responsibility of the manufacturing company to determine such influences of the welding process, such as shrinkage or swelling, and to take them into account if necessary.

The ambient temperature during the welding process changes the geometry of the individual parts to be welded and also of the welded element, but this effect is only temporary. If the membrane element is brought from a hot production hall to a cold construction site after the welding process, it naturally has different dimensions. It is only important to document the temperature during the final inspection of the element dimensions and to take it into account when comparing the target and actual geometries.

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Of course, the ambient temperature during the welding process can have an influence on the welding machine parameters to be set. However, it is up to the manufacturing company to take this effect into account when setting the machine.

2.3.4 Tolerances

The scattering represent a further production-related influence on the pre-stress. This applies in particular to single-layer systems. A distinction must be made between the following scatterings:

- tolerances of the ETFE-manufacturing
- tolerances of the sub-structure (on construction site, before and after membrane assembly)

The permissible tolerances for ETFE film production are to be regulated by the Eurocode for membranes in the process.

The tolerances of the substructure can be divided into production-related component tolerances and building tolerances (e.g. steel substructure). Both types of tolerances can be found in the Eurocode, but they are far from being defined for membrane structures. The Eurocode only offers different tolerance classes. Single-layer ETFE-films only forgive very low deviation from in the nominal substructure if the clamping profiles do not allow adjustment or if there is no possibility of assembling the membranes on the basis of an on-site survey. It is, therefore, strongly recommended that the intended Eurocode for membrane structures defines appropriate tolerance classes for the substructure.

2.3.5 Installation temperature

Whether a correctly manufactured single-layer, mechanically pre-stressed ETFE-film is easy or difficult to install depends on the installation temperature.

At low temperatures, the film is not only smaller but also stiffer. This makes assembly more difficult and increases the risk of damage during the installation process, especially at the points of application of the pulling devices and in the membrane corners.

For this reason, installation at ambient temperatures below + 5°C for films and fabrics is not recommended or even excluded. Among other things, this principle must be applied to all membrane constructions for reasons of occupational safety, not just to single-layer ETFE film systems.

The installation temperature only has a temporary influence on the pre-stress. When the film reaches a temperature of + 23°C again, it has its nominal geometry and thus also its nominal pre-stress, unless other influences are not taken into account.

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Conclusions of the above

In order to approximately achieve the pre-stress states dependent on the load case, the structural calculation of single-layer mechanically pre-stressed ETFE film systems must take the significant influences into account. This applies to all types and to all inspection levels:

- compliance with the given limits of pre-stress
- definition of the minimum and maximum temperature for each load combination
- approach of correct temperature- and product-related mechanical properties
- correction of the cutting geometry in case of significantly different temperatures at cutting
- consideration of the weld shrinkage (depending on the machine and process)
- consideration of manufacturing tolerances
- consideration of the building tolerances of the substructure (optional: adjustable profile or manufacturing based on a survey)

2.4 Water pond verification

Evidence of the water load must be provided for all membrane constructions. The risk of a serious water pond must be excluded.

For mechanically pre-stressed membranes made of fabrics, the water load verification is usually carried out with non-factored loads (γ_f = 1.0 [-]) (deformation verification). This principle is also applicable to mechanically pre-stressed ETFE foils, but only if the influences on the pre-stress of the film are taken into account in the compensation and the pre-stress of the film and of the the supporting ropes are reduced in a proper magnitude and according to EN 1990, as well as the stiffness of the film.

In the case of mechanically pre-stressed ETFE-film systems, plastic deformations (critical residual strains) must be excluded, which could lead to a gradual change in shape and thus to an uncontrolled increase in load and ultimately to failure of the construction. If significant residual strains cannot be safely excluded in one of the design load cases, the water load verification must be carried out with factorized water load (γ_f = 1.5 [-]) in the ultimate limit state (ULS).

In the case of an air inflated cushion, the water pond verification is a bit different. It considers two states:

a) air inflated cushion
b) air deflated cushion

In the first case, the verification is usually trivial, since water runs off immediately on air-filled cushion (if designed well).

If the second case of an air-deflated cushion can only occur if the air supply fails, it has so far been treated as an accidental design situation according to EN 1990. In this case the partial safety factor is γ_f = 1.0 [-] on the impact side and the corresponding load combination factors (Ψ-values) can be applied.

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No rule without exception: If the design snow load exceeds the internal design pressure in the cushion, the air is pushed out of the cushion until a state of equilibrium is established. Depending on the cushions geometry, this is sometimes only achieved when film-layers lie on top of one another. This state is geometrically similar to the evacuated cushion. However, accordingly to EN 1990 this case should not be treated as an accidental design situation, but rather investigated with a partial safety factor γ_f = 1.5 [-] in the ultimate limit state (ULS).

Because of this case distinction to be applied on pneumatic structures only, there is a difference between both types of ETFE-film structures.

Conclusions of the above

For mechanically pre-stressed membranes made of fabrics, the water load verification is usually carried out with non-factored loads (γ_f = 1.0 [-]) (deformation verification). This principle is also applicable to mechanically pre-stressed ETFE foils, but only if the influences on the pre-stress of the film are taken into account in the compensation and the pre-stress of the film and of the the supporting ropes are reduced in a proper magnitude and according to EN 1990, as well as the stiffness of the film.

In the case of mechanically pre-stressed ETFE-film systems, plastic deformations (critical residual strains) must be excluded, which could lead to a gradual change in shape and thus to an uncontrolled increase in load and ultimately to failure of the construction. If significant residual strains cannot be safely excluded in one of the design load cases, the water load verification must be carried out with factorized water load (γ_f = 1.5 [-]) in the ultimate limit state (ULS).

3 Resistance Side

3.1 Material-related effects

The same film products are used for both types. This means that the mechanical material properties of the respective film product do not differ. The material-dependent modification factors must therefore be identical:

k_{age} environmetal effects, material ageing

k_{biax} biaxial effects

k_{perm} effects due to permanent loads (e.g. pre-stress)

k_{long} effects due to long term loads (e.g. snow)

k_{temp} effects due to temperature

k_x not used yet

Conclusion of the above

The modification factors (k_{mod}) consider effects on the resistance side, for example, strength-reducing or strength-increasing influences. These can be material-related or system-related. If it is a material-related effect, the relevant modification factor shall be identical for both systems.

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3.2 System-related effects

Since the same material is used in both systems, the values of material-related modification factors must be identical for cushions and for single-layer structures.

Conclusions of the above

If the effect is not material-related but rather a system-related effect (e.g. model inaccuracies and scale effects), this must also be taken into account on the resistance side according to EN 1990.

If a distinction between pneumatically and mechanically pre-stressed ETFE-film systems should be necessary, a system-related effect can be taken into account with the modification factor k_x [1] which has not been used yet.

4 Failure modes

As known, ETFE-film systems are only subjected to tension in general, in both types. Bending and failure of stability are excluded with the thin films.

With both types of construction, the ETFE-films can fail due to material fatigue if the pre-stress was chosen too low or was not available due to a failure of the air supply (pneumatic cushions).

There are examples of both types of systems in which the film (ECTFE and ETFE) has failed due to material fatigue. A rare number of examples from practice show wind-induced high-frequent bending stresses and finally classic brittle failure of the film (such as glass), which could also be simulated by dynamic (cyclical) fatigue bending tests in the laboratory.

Conclusions of the above

With regard to the failure mechanism of material fatigue, the introduction of a minimum limit values for pre-stress is necessary.

Since single-layer ETFE-films are often combined with ropes (in order to increase the span of the film structure), the focus in such cases must not be exclusively on the pre-stress of the film. Rather, the pre-stress of the primary structure and the ropes, as well as their maximum spans, must be kept in mind.

Material fatigue of the film can be reliably excluded by adhering to minimum limit values for the pre-stressing of the film and the ropes with deformation restrictions of the film, the ropes and the primary structure.

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5 Summary

With regard to the impacts and to the material resistances, single-layer, mechanically pre-stressed ETFE film systems do not differ from multi-layer, pneumatically pre-stressed systems.

However, they differ in the effects of the impacts due to system influences. This difference relates to the effects in the case of plastic deformation (critical residual strains), an associated decrease in pretension and finally the associated increase in the risk of possible water pond formation.

For mechanically pre-stressed membranes made of fabrics, the water load verification is usually carried out with non-factored loads (γ_f = 1.0 [-]) (deformation verification). This principle is also applicable to mechanically pre-stressed ETFE foils, but only if the influences on the pre-stress of the film are taken into account in the compensation and the pre-stress of the film and of the the supporting ropes are reduced in a proper magnitude and according to EN 1990, as well as the stiffness of the film.

In the case of mechanically pre-stressed ETFE-film systems, plastic deformations (critical residual strains) must be excluded, which could lead to a gradual change in shape and thus to an uncontrolled increase in load and ultimately to failure of the construction. If significant residual strains cannot be safely excluded in one of the design load cases, the water load verification must be carried out with factorized water load (γ_f = 1.5 [-]) in the ultimate limit state (ULS).

If the limit values proposed here for the film pre-stress are complied with, the main influences on the pre-stresses are taken into account and the static verifications are fulfilled, there is no risk of plastic deformations with an associated critical reduction of the pre-stress.

The safety concept for multi-layer, pneumatically pre-stressed systems made of ETFE foils can then also be applied to the mechanically pre-stressed single layer ETFE-foil systems. For this, however, it is also essential to limit the geometric deviations in the substructure.

The options of using a profile that can still be adjusted later or of manufacturing the film on the basis of a measurement of the substructure can so far only be realized in exceptional cases.

Should further investigations show that mechanically prestressed single-layer ETFE foil structures require increased safety against plastic deformations, the following options for implementation would be available:

1. The unused modification factor k_x [1] could be used as a modification factor to take system effects into account. However, this factor should only be higher than 1.0 if relaxation effects of the single-layer film should not be excluded already by the introduced safety elements.
2. Optionally, EN 1990 differentiates between γ_m and γ_M on the resistance side: In contrast to the partial safety factor γ_m, which relates exclusively to material-related effects, γ_M also takes systemic effects such as model inaccuracies and scale effects into account. However, such a γ_M would have to refer to the SLS, since the exclusion of irreversible residual strains (plastic deformation) refers to the avoidance of relaxation and yield effects and not to the state of break.

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Annex – Examples

Temporary single-layer systems made of ETFE

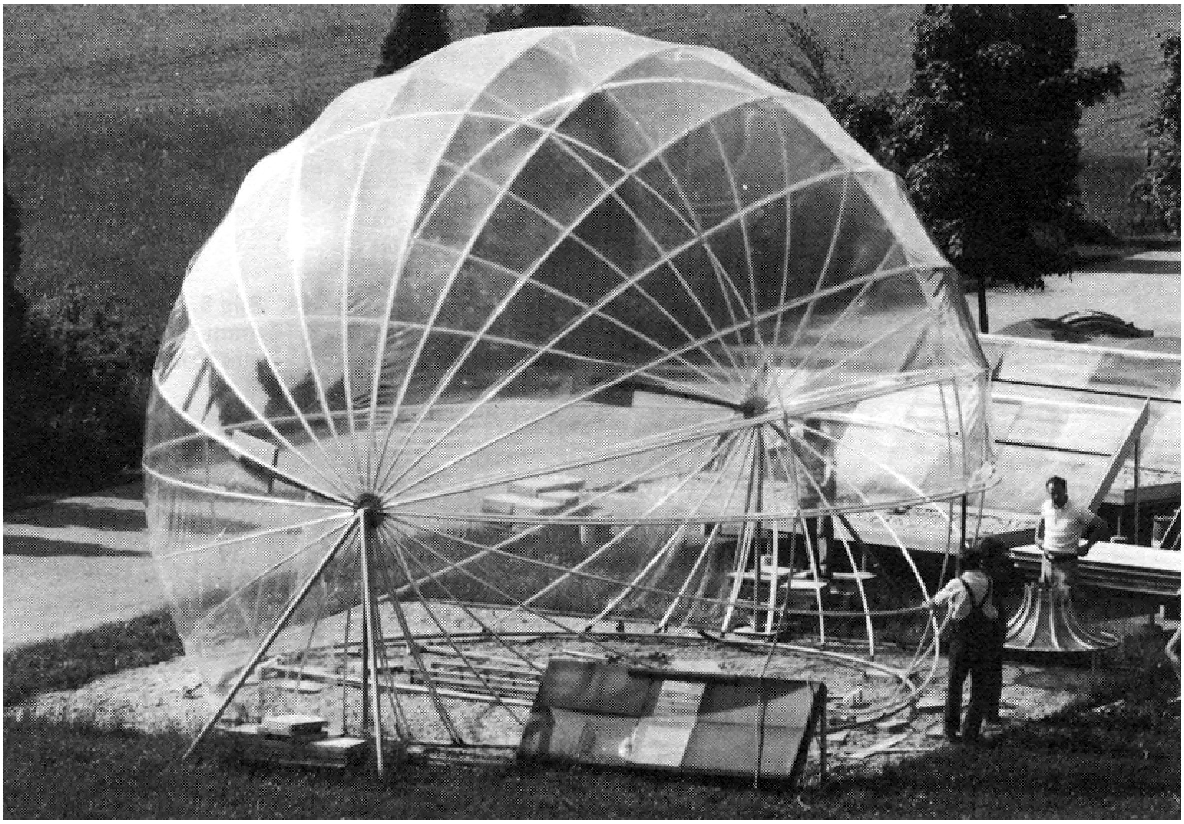

Fig. 1: ETFE-Sphere, temporäry, 3rd Internationale Sun-Forum, Hamburg, 1980, ETFE-film, single lalyer structure, mechanically pre-stressed in combination with slim bended rods, HOECHST HOSTAFLON ET 150 µm, max. distance of the rods approx. 1,0 m, sphere diameter approx. 8 m, heght approx. 6 m, Design: Hans and Jürgen KLEINWÄCHTER, BOMIN SOLAR RESEARCH, Lörrach, Execution: Herbert KOCH, KOIT GmbH, Rimsting [4]

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Permanent single-layer systems made of ETFE

According to the research mentioned above [3], the topic of single-layer, mechanically pre-stressed ETFE-films used for permanent structures was taken up again much later. This was mainly due to the misjudgment that permanent use of ETFE-films as a load-bearing roof or facade element or as a load-bearing building envelope was impossible due to creep and relaxation effects.

The following projects have refuted this assessment, which led to the fact that the single-layer construction method has been widely used to this day and is part of the range of construction methods. The pilot project of permanent construction made of ETFE-film was a small canopy in Prien at lake Chiemsee in Germany in 1999, followed two years later by the information center in Kochel am See. (Fig. 2 and 3)

Fig. 2: Public bath PRIENAVERA, Prien at Lake Chiemsee, canopy, 1999, ETFE-film single layer structure, mechanically pre-stressed, cable-supported, NOWOFLON ET6235 200 µm, 17 fields, total surface area: approx. 200 m², field-size approx. 12 m² in average, architect: ZELLER & ROMSTÄTTER, Traunstein, Structural Design and Engineering: ZELLER, Traunstein, TENSYS Ltd. Bath/UK, realization membrane roof: Koch Membrane Structures GmbH, Rimsting [3]

Fig. 3: E-ON Info Center Walchensee Poower Plant in Kochel, 2001, ETFE-film single layer structure, mechanically pre-stressed, on aluminum girders and wooden (laminated) arches, NOWOFLON ET6235 200 µm, 1 field, total surface area: approx. 391 m², architect: HAUSCHILD & BOESEL, Munich, Structural Design and Engineering: DITTRICH, München, ENGINEERING+DESIGN, Linke & Moritz GbR, Rosenheim, realization membrane roof: COVERTEX GmbH, Obing [3]

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Finally, around 10,000 m² of the grandstand of the AWD-Arena in Hanover (today HDI-Arena) was covered with a transparent ETFE-film roof (Fig. 4) [3], [6].

Fig. 4: AWD Arena (today: HDI Arena), Hanover, grandstand roof, 2005, ETFE-film single layer structure, mechanically 4pre-stressed, cable- and girder-supported, NOWOFLON ET6235 250 µm, 34 fields, total surface area: approx. 10.000 m², architect: SCHULITZ + PARTNER GmbH, Brunswick, Structural Design and Engineering: RFR Ingenieure GmbH, Stuttgart, WEYER Beratende Ingenieure im Bauwesen GmbH, Dortmund, ENGINEERING+DESIGN, Linke & Moritz GbR, Rosenheim, realization membrane roof: WEYSS & FREYTAG Ingenieurbau AG [3], [6]

The design concept applied at the AWD Arena already took into account the temperature dependency of the film in the serviceability limit state (SLS) and in the ultimate limit state (ULS) (Fig. 2.32 in [3]). The principle has proven to be reliable.

A number of single-layer structures made of ETFE-film as a structural element have already followed worldwide, therefore, such as the roof over the PLACE ROGIER in Brussels, Belgium (Fig. 5).

Fig. 5: Place Rogier, Brussels, 2018, ETFE-film, single layer structure, mechanically pre-stressed, NOWOFLON ET6235 250 µm, 3 fields, total surface area: approx. 3000 m², architect: Xaveer De Geyter Architects (XDGA), Brussels, membrane engineering: KONSTRUCT AG, Rosenheim, realization membrane roof: TAIYO EUROPE GmbH, Sauerlach, Foto [5]

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