TensiNet European
Design Guide for
Tensile Structures
Appendix A5

DESIGN RECOMMENDATIONS FOR ETFE FOIL STRUCTURES

TensiNet ETFE Working Group

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1 Botanic Garden Aarhus, Sweden
Ceno-Tec
© Quintin Lake
Manufacturing of cushions: Ceno Tec
Engineering of cushions: form TL
2 Indoor swimming pool in Neydens, France
seele
© Reithmeier on behalf of seele
Manufacturing of 3 layer ETFE-cushion-envelope: seele
3 Dome of the Plaza del Milenio, Valladolid, Spain
IASO
Manufacturing of cushions: IASO SA
Engineering of cushions: Tentech
4 Excel Conference center, London, UK
Architen Landrell
© Edmund Sumner
Design, manufacture and installation: Architen Landrell
Engineering of cushions: Momentum Engineers

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Design recommendations for ETFE foil structures
TensiNet ETFE Working Group

Responsible for the content
Bernd Stimpfle, form TL
Cedric Galliot, Empa
Heidrun Bögner-Balz, Rainer Blum, Jochen Köhnlein, Labor Blum
Helmut Frisch and Sebastian Zehentmaier, Dyneon
James Ward, Architen Landrell
Jan Cremers, Hightex GmbH, Hochschule für Technik Stuttgart
John Chilton, University of Nottingham
Karsten Moritz, seele
Klaus Gipperich, CenoTec
Markus Balz, SBP
Matthew Birchall, Happold
Rogier Houtman, Tentech

Editor
Rogier Houtman, Tentech

A5.1 Description of scope of Annex 5 of the TensiNet Design Guide

This Guide recommends safety requirements which need to be considered for the design, calculation, manufacture, installation, maintenance, operation, examination and testing of ETFE foil structures. This can be applied to double- and multi-layer ETFE cushion structures or single layer tensioned ETFE membrane structures.
The field of application of this Guide includes all kinds of ETFE covered structures. The content of this Guide brings together the different existing concepts as far as possible.

The Design recommendations for ETFE foil structures have been established by the TensiNet ETFE Working group and are a separate Annex of the European Design Guide for Tensile Surface Structures, published by the TensiNet Association in 2004.

A5.2 General Description of ETFE

Production of ETFE raw materials

ETFE, short for Ethylene - Tetrafluoroethylene, is a copolymer of ethylene and tetrafluoroethylene (TFE). TFE is based on the natural mineral fluorspar. It forms a long linear molecular chain as shown in the figure below. The material is first polymerized and then extruded into pellet form.

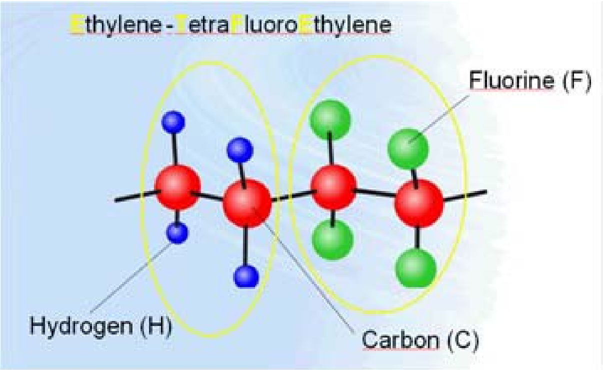


Figure 1, Molecular chain of Dyneon ETFE

Properties of ETFE raw materials

ETFE has excellent chemical, thermal and electrical properties, as well as superior resistance to abrasion and cut-through. It is essential in a myriad of industries such as aerospace, automotive and chemical processing.

Applications include wiring for nuclear plant control rooms, extruded and moulded valves, tubes and pipes, low permeation tubing, radiation resistant film and architectural films.

<u>ETFE fluorothermoplastic is characterized by the following features:</u>

- Wide service temperature range
- Low flammability
- Excellent electrical and mechanical properties
- Very good resistance to solvents and chemicals
- Extremely high resistance to outdoor weathering
- High light transmission in the visible and UV ranges
- Non-stick characteristics
- Excellent tear resistance
- Good stress cracking resistance
- Low permeability
- Good resistance to radiation

<u>ETFE raw materials are sold by the following companies and under these brand names:</u>

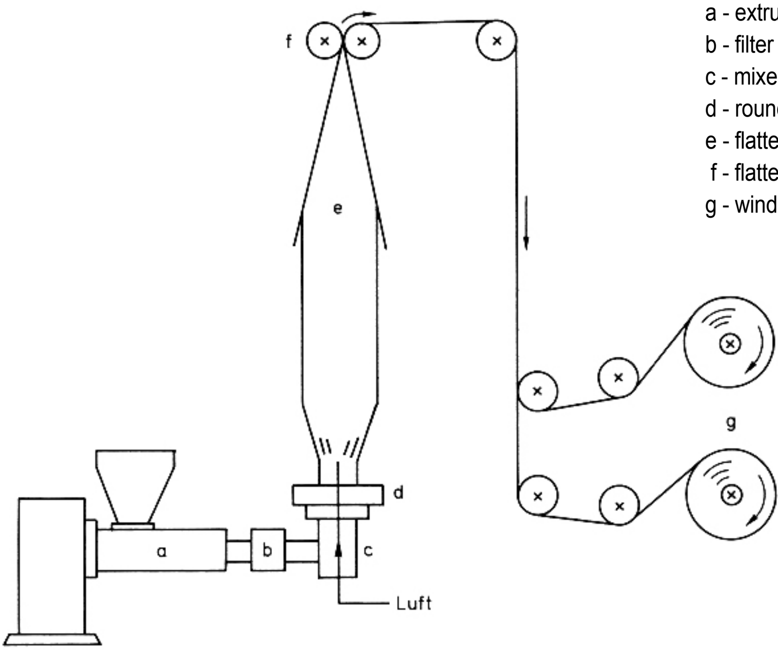
- Asahi Glass (Japan): Fluon ETFE
- Daikin (Japan): Neoflon ETFE
- DuPont (USA): Tefzel
- Dyneon, a 3M company (Germany): Dyneon ETFE (formerly known as Hostaflon ET)


Figure 2, ETFE pellets, AGC

Production of ETFE foil

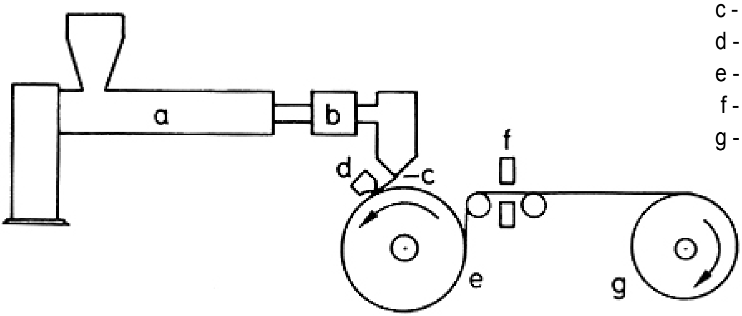
To make ETFE foil, the pellets are heated to approximately 340°C and forced through a machine under pressure. This process is known as extrusion. The hot melt can either be extruded through a round die for blown film or a slit-die for foil. The art of ETFE foil production lies in the right balance of the raw materials used the parameter settings of the extruder, the adjustment of the die and the speed settings of take-off unit and winder.

ETFE foil properties differ between the two production methods. The blown film extrusion method could potentially provide a foil with a greater width, but the production process is more difficult to control. The thickness of the foil is effectively limited to 150 μm and shows more variation in thickness. There are also very apparent lines and the foil is less isotropic.



a - extruder
b - filter
c - mixer
d - round die
e - flattening of foil
f - flattening roller
g - winder

Figure 3, blown film extrusion method



a - extruder
b - filter
c - flat die
d - air brush
e - cooling roller
f - thickness control
g - winder

Figure 4, slit-die film extrusion method

Extrusion through a slit-die results in a much better foil that shows less variation. Foil thicknesses of up to 300 µm can be realized and the foil is much more transparent and free of defects.
Therefore cast extrusion foil is the foil of choice in every major ETFE foil construction project.
After extrusion, the foil can be printed or otherwise surface treated, depending on the customer's requirements.

ETFE foil - General properties

Property	*Approximated value / range*	*Unit*
Specific gravity	1.75	g/cm^3
Notch impact test	15	kJ/m^2
Ball hardness	31-33	N/mm^2
Shore hardness	67-73	Shore D
Limiting Oxygen Index	35	%
Shrinkage at 150° C, 10 min.	2.5	%
Coefficient of friction (dry, against steel)	0.2-0.5	-
Melting point	255-280	°C
Coefficient of linear expansion 0-100°C	$11\text{-}14 \times 10^{-5}$	m/m/K
Maximum service temperature	150	°C
Tensile modulus of elasticity	1100	MPa
Yield point at 23°C	21	MPa
Tensile strength at 23°C	50	MPa
Elongation at break at 23°C	450	%
Tensile strength at 150°C	10-20	MPa
Tear propagation force at 23°C	450	N/mm

Advantages of ETFE foil

- Very high transparency in the visible range. A substantial amount of UV radiation (UV-A and UV-B) also passes through the foil (Fig. 5)
- Very strong and tear resistant
- Does not maintain fire (B1 class fire resistance)
- No mechanical or visible aging under stress, the foil does not become brittle over time
- Has been proven to last at least 20 years
- Self-cleaning due to the fact that dirt cannot attach to the foil and is washed away by rain
- Abrasion resistant
- 100% recyclable
- Very lightweight
- Small defects are easy to repair with tape.
- Fluoropolymers have the lowest coefficient of friction of any plastic material
- ETFE foil can be (colour) pattern printed
- Hail resistant, in cushion applications - ETFE foil complies with the Swiss standard SIA 280 for hail resistance
- Does not react with other substances

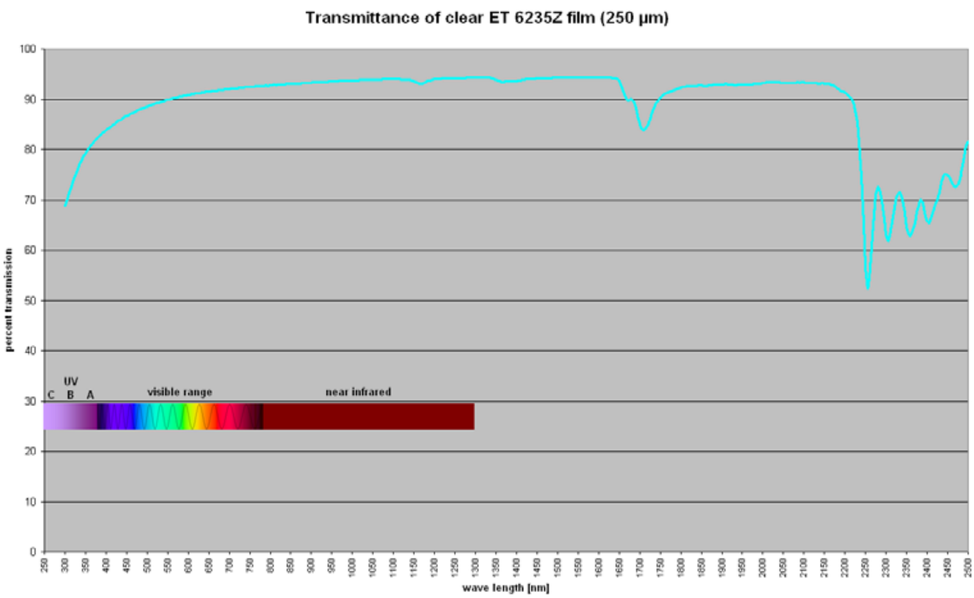


Figure 5, Light transmittance of ETFE film, giving the % of transmission for a 250 µm film in function of the wavelength [nm], Dyneon GmbH

Disadvantages of ETFE foil

- Relatively weak for a membrane material
- Creep is a major factor. 1 - 2% additional strain under elastic load as a result of creep (Fig. 6)
- Properties change with temperature (Fig. 7)

- Easy to cut with a sharp object, public access to the foil must be avoided to minimize the risk of damage by vandalism
- Does not provide good protection for UV sensitive materials - including human skin with long exposure (e.g. workers in an ETFE covered shopping mall or atrium)
- Curved ETFE foil surfaces distort the view
- Does not bond well with other materials
- Does not have the transparency of glass (translucent rather than transparent)

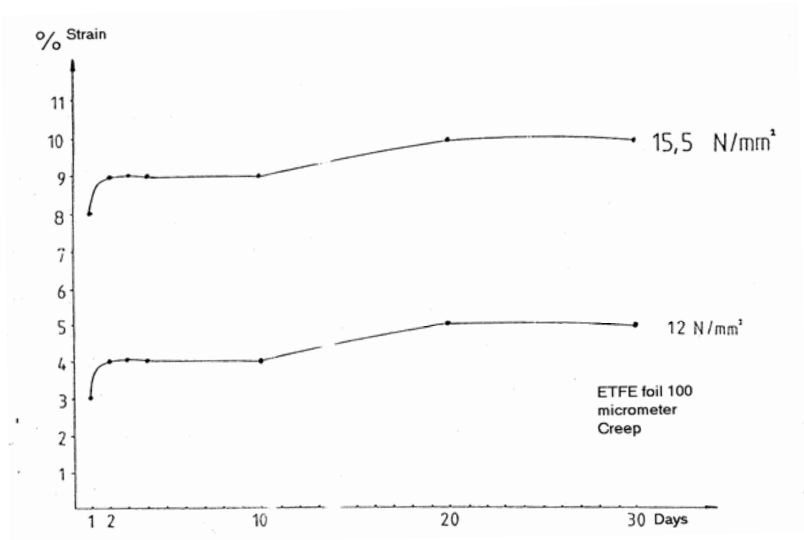


Figure 6, Creep research by Hoechst 1983, ETFE foil Hostaflon ET-6235, 100 µm, T=23°C

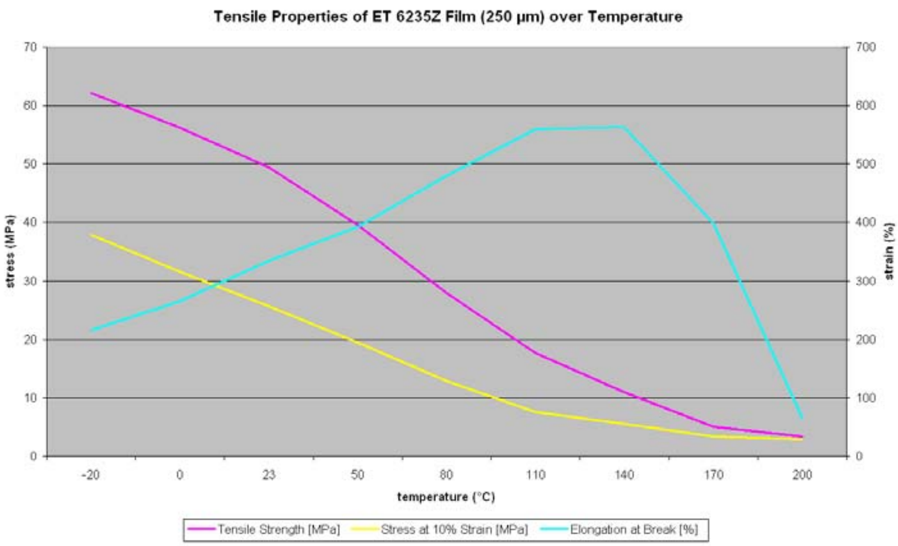


Figure 7, Tensile properties of ETFE film against temperature (-20° to +200°C), ETFE foil NOWOFLON ET 6235 Z

Application of ETFE foil

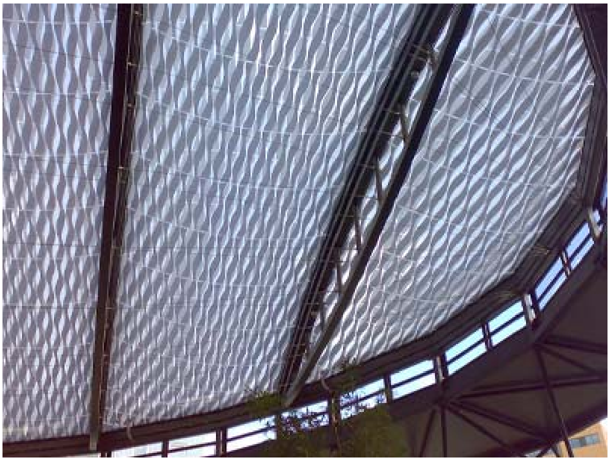


Figure 8, 4-layer cushion with movable inner layer, JinSo pavilion Amsterdam (Buitink Technology)

When used in structures, EFTE foil is often used in a cushion form. An ETFE air cushion consists of two or more layers of foil, an enclosing framework and pressurized air between the layers. The pressure is regulated between 200 and 750 Pa by a small air pump, depending on the wind or snow conditions. Cushion applications range from two-layer cushions to the more efficient multi-layered dynamic 'intelligent' applications in roofs and façades.

Figure 9, Single layer ETFE, Chamber of Commerce, Wurzburg (seele cover)

ETFE foil welding

Plastic foils are limited in width, for instance slit-die extruded ETFE foil manufactured by Nowofol has a maximum width of 1.55 m. So for wider dimensions some form of joining two layers of ETFE foil has to be established. ETFE foil can be bonded by adhesives or it can be melt bonded.

Bonding by adhesives requires a thorough preparation of the ETFE foil. Chemical etching, corona3 or flame treatment is necessary to prepare the surface of ETFE to allow adhesive bonding. The adhesive can be of any suitable compound but must be a reactive adhesive, or it will not bond well. The necessary preparation, the low Ultra Violet tolerance of adhesives and the low strength of the bond made by adhesive makes this type of bonding more suited for laboratory use than for construction purposes.

ETFE responds well to melt bonding and can be bonded in this way with untreated aluminium, steel, copper and itself. Melt bonding is the most used method for welding foil to itself. The strength of a melt-weld depends on experimental-determined temperature, pressure and contact time. The success of this type of bonding in application is also dependent on the design of the joint, spotlessness of the material, correct adjustment of the equipment, skill of operative.

A5.3 Uni-axial and biaxial mechanical properties of ETFE foils

This paragraph is partially taken from the article of Cedric Galliot on “Uni-axial and biaxial mechanical properties of ETFE foils“ [9].

The mechanical behaviour of ETFE foils is typical for polymers and presents non-linearity’s, large plastic deformations [2,10,12] as well as rate and temperature dependency [2,13]. Stress-strain curves obtained from ETFE foil uni-axial tensile tests exhibit two points where the stiffness significantly changes, denoted as two yield points [2,10,14]. For design purposes, the initial behaviour of ETFE foils is generally considered and modelled as linear elastic isotropic.
The opportunity of using the second yield stress for structural design has been investigated by Kawabata [14]. His study on ETFE foil hardening is based on cyclic loading performed up to the second yield point. The foil produces residual plastic strain and after a certain number of repetitions its behaviour no longer changes. The final material behaviour is linear elastic up to the second yield stress. If these residual strains are not recoverable, then it would be feasible to use the second yield stress as a design stress. This is seen as a future perspective when more research is carried out on this subject.
For the design of structures with ETFE foils, it is also very important to take into account the effect of strain-rate and temperature that strongly affect the material behaviour. For example, Moritz [2] has shown that the yield stress decreases with increasing temperature and increases with the strain rate. These effects are usually taken into account by applying reduction factors for the calculation of the design stress.

The mechanical behaviour of ETFE foils is generally measured on uni-axial tensile test machines [2,12,12,14,15], in which case tests are often carried out in two different directions in order to assess the influence of the foil manufacturing process on the mechanical properties. ETFE foils are extruded and it is expected that the material behaviour in the machine (extrusion direction) and transverse direction would not be exactly identical. There is also an increasing interest in biaxial tensile loading as it allows consideration of the biaxial stress conditions that exist in foil constructions.

Stress and strain information directly obtained from the test results is the so called engineering stress and engineering strain. Most design concepts are based on engineering stress and strain. Depending on the research that is done individually, uni-axial or biaxial, a design concept is derived. To compare those concepts, in fact, is difficult. Galliot has investigated uniaxial and biaxial tests, both burst tests and normal biaxial tests and compared the tests based on the true stresses. True stresses take into account the change of thickness of the foil due to the strain. A very surprising result is shown in figure 11 where different test methods do show the same result. This result suggests that all mentioned testing methods in the end have more or less the same result unless the true stress and strain are used.

The design concepts discussed in chapter A5.4 are all based on engineering stresses. It therefore depends on the specific concept which approach is taken.

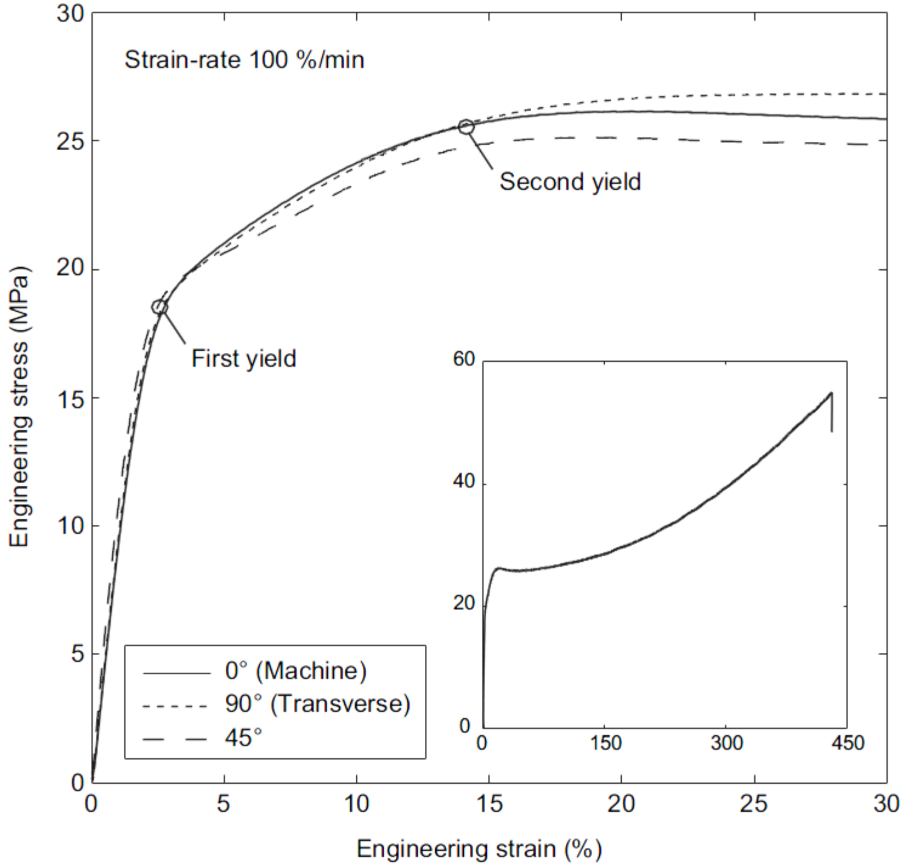


Figure 10, Typical uni-axial stress-strain curves at different specimen orientations

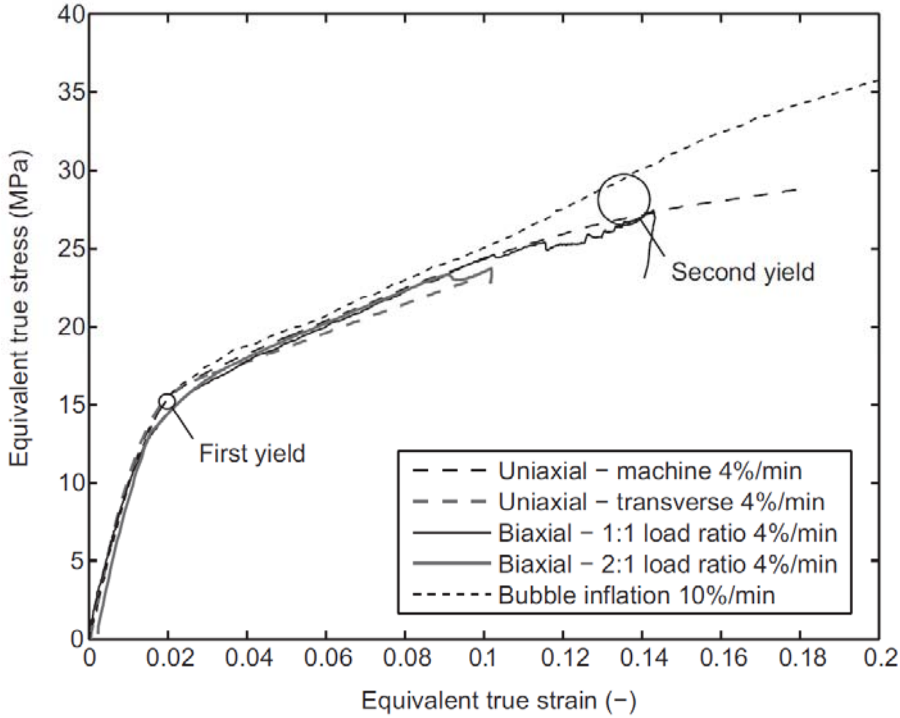


Figure 11, comparison of equivalent true stress and strain of uniaxial and biaxial tests.

A5.4 Structural design basis and safety criteria for ETFE cushions

As the application of ETFE is still relatively young, there are several approaches used among companies involved in ETFE foil structures. The aim of this chapter is to compare the different design concepts and find a minimum level of safety criteria to be used.
Several issues are important in this comparison. In the past, the approach of ‘Permissible Stress’ has been in use. It is a straightforward approach that puts all the safety factors on the material side (Resistance side). Nowadays the approach of the Eurocodes is more commonly accepted, the ‘Limit State’ approach. This method works well for structures that are ‘linear-elastic’ in their behaviour, which is not the case for membrane structures (See Chapter 6.1 of the TensiNet Design Guide and EN-1990:2002 6.3.2 (4)). In the methods described here it turns out there is a mixture of methods, trying to deal with this issue.

A5.4.1 Recommendations J.W.J. de Vries (TU Delft)

Jos de Vries has investigated mono-axial and biaxial properties of ETFE foil with the aim to define a design concept based on the “Limit State” approach. An important issue has been the determination of a yield point and creep limit. As the material behaves in a non-linear manner, a long- and short-term load is defined.

Reduction factors in Serviceability Limit State (SLS)

σ_d = $\sigma_{rep} / \gamma_m * k_{mod}$
σ_d = Design stress for ETFE foil
σ_{rep} = Representative stress for ETFE foil, to be determined (approximate values for 1:1; 12 N/mm^2, for 1:2 / 2:1; 15 N/mm^2)
γ_m = Safety factor for material uncertainties
k_{mod} = Modification factor for temperature and creep
γ_m = 1

Deformation criteria	Load duration	Temperature (°C)	k_{mod}
Adjusted for limited permanent deformation (< 5% strain)	Less than 15 min	t < 20	1.00
		20 < t < 30	0.91
		30 < t < 50	0.71
	More than 15 min	t < 20	0.84
		20 < t < 30	0.77
		30 < t < 50	0.60

Table 1: Reduction factor k_{mod} depending on temperature and load duration

The focus of the research was on the Serviceability Limit State. It is assumed that the Ultimate limit State is not the restrictive state. Therefore no recommendations are mentioned for the ULS.

Important issues addressed here are the temperature dependence of the creep level and strength of the foil.

A5.4.2 System based on Dissertation von MINTE

MINTE[1981]: "The mechanical behaviour of connections of coated chemical fibre weave"
Minte has done research on the relation between biaxial and mono-axial strengths of woven fabrics. He has suggested a system of reduction factors A_0 to A_3, later extended with A_4 and more values when appropriate. Also a safety factor S was included, which makes this system a good example of the "admissible stress" method.
For the full explanation of the system of Minte for woven fabrics the reader is referred to chapter 6.2.3 of the Tensinet Design Guide.
The basis of this system, or parts of the system, are used by others to adapt it into a system for ETFE foil.

A5.4.3 ETFE Foil design concept developed by form TL

Form TL has developed an approach that focuses on the remaining strain of the foil, as this is a very important issue for ETFE foil structures. This also can be seen as a method addressing the Serviceability Limit State. Form TL formulates their approach as follows: ETFE foil is an isotropic material. Due to the production method, there are slight differences in properties in the extrusion direction and perpendicular to the extrusion direction, but these differences are negligible for construction purposes. Unlike coated fabric, the foil suffers large deformations, and reduces the stress due to this deformation to some extent. Due to this behaviour for foil a different design concept must be applied. The most important criterion is the remaining strain in the foil (SLS). Due to the very high breaking strain, the breaking point of the foil cannot be reached in a structure under normal conditions (ULS).
Stress strain diagrams of Nowofol done with the 200µm foil at 23°C show a 10% strain-stress of 21 N/mm². Furthermore the foil shows linear elastic behaviour up to a stress of 15 N/mm².

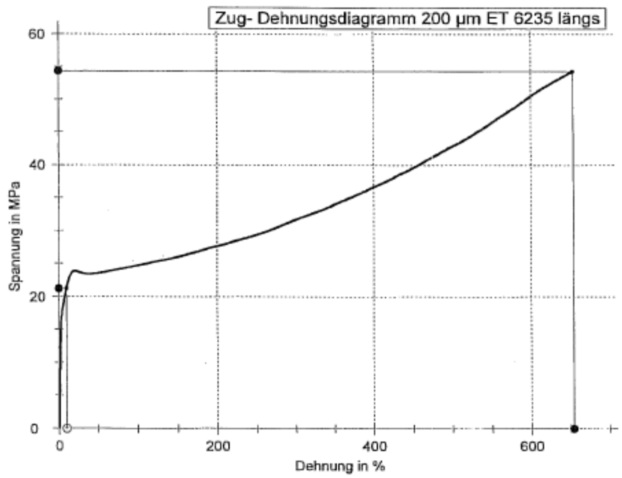


Figure 12, Stress strain diagram for Nowofol 200µm foil

To minimize the remaining strain in the foil, a safety factor η_{10} is determined with 21 / 15 = 1.4 rounded up to η_{10}**= 1.5**.

For different projects form TL has determined, for 100μm, 150μm and 200μm thick foils, short-term tests where the 10% strain-stress, the yield stress and the breaking strength have been determined.

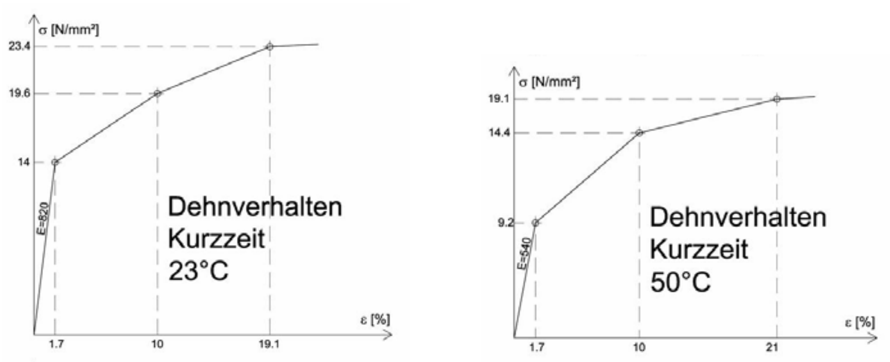


Figure 13, Simplified stress strain diagram uni-axial strip

In all these projects the 5% fractile of the 10%-strain-stress has been used, as shown below:

23°C: $\sigma_{10;\ 23°C;\ 5\%}$= 19 N/mm²
50°C: $\sigma_{10;\ 50°C;\ 5\%}$= 16 N/mm²
70°C: $\sigma_{10;\ 70°C;\ 5\%}$= 11 N/mm²

Furthermore form TL has introduced a reduction factor $\mathbf{A_2}$ for environmental conditions. This factor has been determined in one of their projects with $\mathbf{A_2 = 1.05}$.
This leads to the following design concept for ETFE foil:

$\eta = \sigma_{10;xx°C;5\%} / (\sigma * A_2) \geqq 1.5$

Based on this we have determined the following values for the admissible stress [kN/m]

thickness temperature	100μm	150μm	200μm	250μm	300μm
23 °C	1.2	1.8	2.4	3.0	3.6
50 °C	1.0	1.5	2.0	2.5	3.05
70 °C	0.7	1.05	1.4	1.75	2.10

Table 2: Admissible stress [kN/m] for different foil thicknesses

As the foil can be heated up, depending on the different load cases and the possible elevated temperature, the appropriate reference value must be used. Due to its behaviour, the ETFE cannot heat up more than 50°C due to solar radiation. With numerical simulations form TL has determined under worst conditions a maximum temperature of 48.5°C.
Biaxial tests show a much stiffer behaviour, but the remaining strain is approximately at the same stress level, therefore the previously mentioned values are reasonable for the dimensioning of the foil.

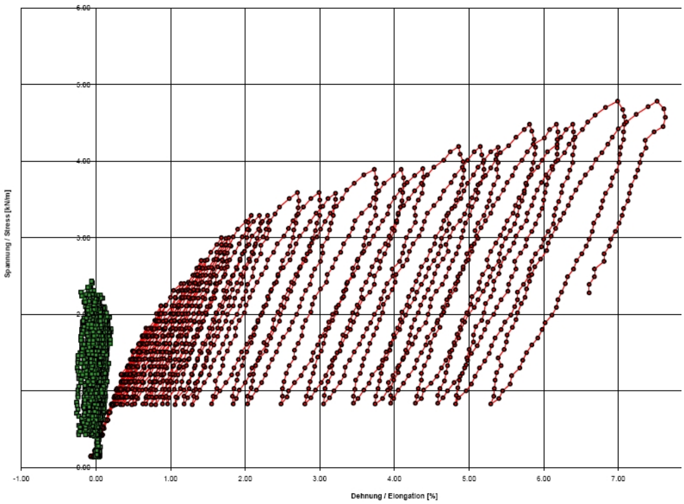


Figure 14, biaxial behaviour with on the x-axis the elongation in % and on the y-axis the stress in kN/m

A5.4.4 ETFE foil design concept developed by Karsten Moritz (seele)

The philosophy of Karsten Moritz is to follow the approach of the Eurocode as far as possible. His safety concept includes separated safety factors on resistance side and on exposure side. He differentiates the equations in serviceability limit state (SLS) and ultimate limit state (ULS). The limit in the ULS refers to the tensile strength; the limit in the SLS refers to the stress at yield. Limits refer to the stresses or strengths in welded specimen (in SLS yield-stress is identical for specimens with and without welding). Therefore the quality of the project-specific production of the weld influences the ULS-equations.

His concept includes reduction factors according to the A-factors originally defined by Minte (A_0 ... A_4). The values are based upon a lot of mono-axial and biaxial tests on ETFE-foils and weldings. He carried out these tests during his research at the TU of Munich (dissertation ETFE-Folie als Tragelement, 2007 [2]). An additional reduction factor A_S considers the reduction in tensile strengths of welded seams compared to the base ETFE-material. This factor depends on the quality in the welding-process of the specific manufacturer. The amount of this factor has to be demonstrated by the specific manufacturer's quality control.

Lars Schiemann tied his work (dissertation Tragverhalten von ETFE-folien unter Biaxialer Beanspruchung, 2009 [6]) to the work of Moritz (both at the TU of Munich). Schiemann used bursting tests to examine the reduction factor A_0 for biaxial exposure in detail ($A_{0,Moritz}$ = 1.2, $A_{0,Schiemann}$ = 1.15). This results in slightly higher values in the ultimate limit states (ULS).

The concept of Moritz can be applied in all climatic zones by adjustment of the thermal reduction factor A_3 to the local conditions. The given relationship of mono-axial and biaxial parameters in SLS and ULS allows a project specific quality control based on mono-axial tests at 23°C mostly. Biaxial tests have to be done only if special requirements exist or irregularities occur.

At first, the characteristic value of the resistance of the foil is determined:

R_k = characteristic value of the resistance = $R_{k,\,0.05}$ / A_{mod}

$R_{k,0.05}$ = 5% fractal of short term tensile strength

$A_{mod} = A_0 \times A_1 \times A_2 \times A_3 \times A_4 \times A_S$

A_0	The reduction factor is meant to take into account reduction of the mono-axial strength caused by biaxial (multi-axial) plane stress conditions. Both for the tensile strength and yield stress at T = + 23°C
A_1	The reduction factor is meant to take into account the reduction of the strength of the mono-axial determined strength values caused by long-term and permanent load
A_2	The reduction factor is meant to take into account the reduction of the strength of the mono-axial determined strength values caused by influences like UV-light, moisture etc. It is dependent on the expected situation at the building location and the reference period.
A_3	The reduction factor is meant to take into account the reduction of the strength of mono-axial determined strength values at 23°C caused by the increase of temperature. ***
A_4	The reduction factor is meant to take into account the reduction of the strength of mono-axial determined strength values caused by production inaccuracies.
A_s	The reduction factor is meant to take into account the reduction of the strength of mono-axial determined strength values caused by welding.

Table 3: A-factor description

Karsten Moritz has carried out extensive research on the following reduction factors. For the full explanation of this the reader is referred to the theses from Moritz [2] and Schiemann [6]. As a result, the following values are defined:

	Reduction of strengths caused by	ULS, $f_{u,k,SN,0.05}$	SLS, $f_{y,k,0.05}$
A_0	Multi-axial stress	1.2 (1.15*)	1.4
A_1	Short term / long term / permanent loading	1.0 / 1.3 / 1.8	
A_2	Environmental influences	1.1	1.0
A_3	Temperature change (T = +40°C) ***	1.2	
A_4	Production inaccuracies	1.0	
A_s	Base material/weld	1.57 **	1.0

* Schiemann [6]

** dependent on the tensile strength of the weld

*** The reduction factor depends on the maximum temperature of the considered layer. The maximum temperature depends on the local ambient conditions at the specific load case. A diagram of the temperature-dependence of A_3 is given by figure 2.27 in [2].

Table 4: A-factor values

Also a number of mono-axial tests were carried out to determine the characteristic values (5%-fractal-values) of yield strengths and breaking strengths for basic ETFE-materials (AGC, NOWOFOL) and the welded seams as well. They are given as follows.

	5%-fractal values of mono-axial strengths of ETFE-Foil at T=23°C [2]
mono-axial stress at yield (2. yieldpoint) at T=23°C (material and weld)	$f_{y,k,0.05,+23°C} = 21\ N/mm$
mono-axial tensile strength of material at T=23°C	$f_{u,k,0.05,+23°C} = 47\ N/mm$
mono-axial tensile strength of weld at T=23°C	$f_{u,k,SN,0.05,+23°C} = 30\ N/mm$*

* example dependent on the tensile strength of the weld

Table 5: 5%-fractal values of mono-axial strengths of ETFE foil at T=23°C

	5%-fractal values of mono-axial strengths of ETFE-Foil at T=3°C [2]
mono-axial stress at yield (2. yieldpoint) at T=3°C (material and weld)	$f_{y,k,0.05,+3°C} = 25\ N/mm$
mono-axial tensile strength of material at T=3°C	$f_{u,k,0.05,+3°C} = 50\ N/mm$
mono-axial tensile strength of weld T=3°C	$f_{u,k,SN,0.05,+3°C} = 33\ N/mm$*

* example dependent on the tensile strength of the weld

Table 6: 5%-fractal values of mono-axial strengths of ETFE foil at T=3°C

The above mentioned values are characteristic values. To arrive at design values, also a partial safety factor on resistance side γ_m needs to be determined: $R_d = R_k / \gamma_m$

	$\gamma_{m,\ ULS}$	$\gamma_{m,\ SLS}$
basic and exceptional combinations, geometrical imperfections	1.1	1.0

Table 7: γ_m values for ULS and SLS

These values result in a set of equations for the structural design of ETFE-foils:
Design values of the resistance of the foil including weld in Ultimate Limit State (ULS)

$$R_{d,\,SN,ULS,Ws} = \frac{f_{u,k,F,\,0{,}05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1{,}1 \cdot 1{,}2 \cdot 1{,}0 \cdot 1{,}1 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}57} = 20{,}62\ N/mm^2$$

$$R_{d,\,SN,ULS,S} = \frac{f_{u,k,F,\,0{,}05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{50}{1{,}1 \cdot 1{,}2 \cdot 1{,}3 \cdot 1{,}1 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}57} = 16{,}87\ N/mm^2$$

$$R_{d,\,SN,ULS,Pnom} = \frac{f_{u,k,F,\,0{,}05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1{,}1 \cdot 1{,}2 \cdot 1{,}8 \cdot 1{,}1 \cdot 1{,}2 \cdot 1{,}0 \cdot 1{,}57} = 9{,}54\ N/mm^2$$

w_s = wind suction, s = snow, p_{nom} = inner pressure

Design values of the resistance of the foil including weld in Serviceability Limit State (SLS)

$$R_{d,\,SN,SLS,Ws} = \frac{f_{y,k,F,\,0{,}05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1{,}0 \cdot 1{,}4 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}0} = 15{,}00\ N/mm^2$$

$$R_{d,\,SN,SLS,S} = \frac{f_{y,k,F,\,0{,}05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{25}{1{,}0 \cdot 1{,}4 \cdot 1{,}3 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}0 \cdot 1{,}0} = 13{,}73\ N/mm^2$$

$$R_{d,\,SN,SLS,Pnom} = \frac{f_{y,k,F,\,0{,}05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1{,}0 \cdot 1{,}4 \cdot 1{,}8 \cdot 1{,}0 \cdot 1{,}2 \cdot 1{,}0 \cdot 1{,}0} = 6{,}94\ N/mm^2$$

w_s = wind suction, s = snow, p_{nom} = inner pressure

The resistances R_d should be compared and be larger than the design load F_d: $R_d > F_d$
The above is taken from the thesis of Karsten Moritz [2]. The author points out that the design concept is applied only if the material properties of the used ETFE-foil comply with this concept and if the qualities of material and welded seams are ensured by an adequate quality assurance.

A5.4.5 Some values from Buro Happold (indicative)

Buro Happold has been involved in some ETFE projects and based on that experience, they have formulated values to be used for ETFE. There is no temperature effect mentioned for long or short term load. Therefore these values are seen as theoretical values at T = 23°C.

Thickness t [µm]	Weight [g/m²]	SLS $f_{y,d}$ [N/mm²]	ULS $f_{u,d}$ [N/mm²]
80	140	12.5	18.75
100	175	13.0	18.0
150	263	13.3	18.7
180	315	12.7	18.3
200	350	13.0	18.5
225	394	12.8	18.2
250	438	13.2	18.4

Table 8: Design values for $f_{y,d}$ and $f_{u,d}$

As an average $f_{y,d}$ value, 12.9 N/mm^2 can be taken. As an average $f_{u,d}$ value, 18.4 N/mm^2 can be taken. A typical pre-stress can be taken as 8-10 N/mm^2.

A5.4.6 ETFE foil design concept developed by Klaus Saxe (ELFF)

Klaus Saxe has carried out extensive research on the properties of ETFE foil [20]. As he is running the Essener Labor for Lightweight structures, he also has testing facilities at his disposal. Below is listed a summary of his publication in [20].
The basis of the approach of Saxe is that of the Eurocode 1, with which he emphasizes that the chosen design concept should correspond. He distinguishes between SLS and ULS. In the design concept both ETFE cushions and single-layer ETFE are incorporated.

Mechanical properties:
Monoaxial tests show less stiff behaviour than biaxial test. Therefore, and because most ETFE foil structures have biaxial stress behaviour, a biaxial test method is chosen for the research. The influence of temperature on the mechanical properties is considerable. Four temperature levels are taken into account: -25°C, 0°C, 23°C, 35°C. E-moduli and reversible creep can be obtained for these different levels.
Repeated loading is investigated; stiffening of the foil takes place at higher load levels. Creep is investigated biaxially at different load levels. Also at higher load levels, the strain tends to an asymptote. To investigate these asymptotes further, relaxation tests are carried out. Starting with a temperature of -25°C and ending at 35°C, 50% of the tension is relaxed for each load level.
The design concept is based on the capacity check in the Ultimate limit state and in the Serviceability Limit State.
In the ULS it is stated that the breaking strength of the connections is critical. The capacity of for example welds or connections should be tested monoaxially for each project at the different temperature levels. The 5% fractile value of these results ($X_{5\%}$), should be compared with the action.

ULS:
$E_{d(T)} \leq R_{d(T)}$
$E_{d(T)} = \text{SUM}\ \gamma_{G,i} * G_{k,i} + \gamma_{Q,1} * Q_{k,1} + \text{SUM}\ \gamma_{Q,i} * \psi * Q_{k,i}$
$R_{d(T)} = R_k / \gamma_m = X_{5\%} / \gamma_m$
With "+" means: "in combination with"
$E_{d(T)}$: Temperature dependent design value of the action
$R_{d(T)}$: Temperature dependent value of the resistance
γ_G, γ_Q: Partial load factors
G_k: Characteristic value of a permanent action
$Q_{k,1}$: Characteristic value of main variable action
$Q_{k,i}$: Characteristic value of other variable actions
$X_{5\%}$: 5% fractile value of pending material property
γ_m: Partial safety factor of building part property

With this set of formula's it is possible to determine the required capacity of the $X_{5\%,needed}$ for connections and junctions.

It is also possible to determine the required capacity by means of the Characteristic value of the Resistance $E_{k(T)}$. This is because the interaction of partial load factors Υ_G and Υ_Q often lead to a kind of average value of $\Upsilon = 1.4$. Combined with the partial safety factor $\Upsilon_m = 1.5$, the product of these values leads to a global factor $\Upsilon_{global} = 2.1$:

$X_{5\%,needed} \geq \Upsilon_{global} * \max E_{k(T)}$.

Common practice hereby is to reduce the Υ_{global} from 2.1 down to 2.0 or 1.9 in case of ETFE cushions as stresses in the cushion reduce when caused by strain the curvature in the cushion increases.

For the SLS is stated that the deformations are seen as normative. So therefore the characteristic values are compared.

$E_{k(T)} < R_{k(T)} * k_{mod\ (biax,\ load\ durarion)}$

Typical values for $R_{k(T)}$ are:

$R_{k(0°C)} = 15.0\ N/mm^2$

$R_{k(23°C)} = 12.0\ N/mm^2$

$R_{k(35°C)} = 10.0\ N/mm^2$

Distinction is made between several load duration classes: short term, mid-term and long term. The appropriate k_{mod} values should be chosen according to the load duration.

Upper limit short term load: $k_{mod(biax,\ short\ term)} = 1.8$

Lower limit long term load: $k_{mod(biax,\ long\ term)} = 0.5$

How these values should be chosen in intermediate situations or in which situations the above values ought to be used, is not revealed and open for discussion. The experience of others is appreciated to evaluate the above mentioned approach.

A remark is made about the determination of the E-modulus. This value is also depending on the temperature and the biaxial stress ratio.

Conclusion

The approach of Klaus Saxe seems rather comparable to the other described methods. However it is not clear how the k_{mod} factors can be evaluated yet. Therefore it is not listed in the comparison in A5.4.7

A5.4.7 Comparison

To compare the different approaches, there are several aspects to take into account. Temperature is an important issue, as well as the duration of the load. Four different aspects will be compared between the different approaches. These are only aspects of a load combination. It is left to the engineering judgement of the reader to determine for each specific situation the correct combination of load cases and reduction factors.

- Permanent load at a temperature of 40°C (moderate climate indoor/outdoor). A permanent load is caused by the inner pressure on the cushion, resulting in a pre-stress of the foil. Especially in roof structures, the lower foil will be heated up by the internal environment and reflection of light.
- Long-term load at a temperature of 3°C. This normally is caused by snow load. When there is snow on top of the cushion, the foil(s) that is (are) in contact with the snow will have a low temperature.

- Long-term load at a temperature of 23°C. This can be caused by a temporary rise in the inner pressure due to snow load or wind load.
- Short-term load at 23°C. This is normally caused by wind load. It is assumed that the ETFE foils that are exposed by the wind cool down rapidly.

The comparison is made for both the ULS and SLS.

SLS	De Vries $f_{y,d}$ [N/mm^2]	form TL $f_{y,d}$ [N/mm^2]	Moritz $f_{y,d}$ [N/mm^2]	Happold $f_{y,d}$ [N/mm^2]
Permanent load 40°C	7.2	7.0	6.9	-
Long-term load 3°C	10.8	15.5	13.7	-
Long-term load 23°C	9.2	10.0	11.5	12.9
Short-term load 23°C	12.0	12.5	15.0	-

ULS	De Vries $f_{y,d}$ [N/mm^2]	form TL $f_{y,d}$ [N/mm^2]	Moritz $f_{y,d}$ [N/mm^2]	Happold $f_{y,d}$ [N/mm^2]
Permanent load 40°C	-	-	9.6 (10.1*)	-
Long-term load 3°C	-	-	16.9 (17.8*)	-
Long-term load 23°C	-	-	15.9 (16.5*)	-
Short-term load 23°C	-	-	20.7 (21.5*)	18.5

* The higher limits (in brackets) are based upon the slightly lower reduction factor A_0 for biaxial exposure ($A_{0,\ Schiemann}$ = 1.15) examined by a number of bursting tests carried out by Schiemann, L., 2009 [6]. These factors have been implemented into the safety concept from Moritz, 2007 ($A_{0,\ Moritz}$ = 1.2) [2].

Table 9: Comparison of design values for SLS and ULS

It must be noted that the values above are based on air supported ETFE foil cushions. This incorporates a certain forgiving behaviour of ETFE that is not described fully yet. When a single layer mechanically pre-tensioned system is used, the material is not forgiving at all and lower values have to be used. See chapter A5.6 on recommendations for single-layer ETFE foil structures.

The comparison above shows the importance of the temperature and time aspects. However there are significant differences between the methods. For permanent load at 40°C each method has quite a similar outcome. The reason for this will be the observable occurring creep. At low temperatures there is much more deviation.
How to deal with long-term load depends on the acceptance of small deformation. This can be a reason for small deviations between different approaches, although the differences become smaller with rising temperature.
The difference in outcome with short-term load has to do with the interpretation of the second yield point in the stress-strain curve and the amount of recovery of the material that is taken into account. As stated above, for mechanically tensioned foil structures, a lower value would be advisable.
The largest difference can be found when the ULS values are examined. These values are only a little higher than the SLS values suggested by the same authors, but do have to be compared with a design load, that means a characteristic value multiplied by a load factor according to EN 1990.

Assuming that the same load cases are investigated for both ULS and SLS, this means the ULS values will be restrictive. The aspect of the strength of the welds that is taken into account in the ULS values plays an important role. As this is not taken into account at all in the other methods, it might be a point of discussion.

Conclusion

The different presented methods show a clear similarity and indicate on the other hand the different approaches that are possible. Therefore it is advised to stay within the range presented below and use one's own engineering judgment to decide from case to case what is appropriate. Moreover not all values are coming from a comparable number of tests. Therefore the values below are indicated within a range.

SLS	Range $f_{y,d}$ [N/mm^2]
Permanent load, 40°C	6.9-7.2
Long term load, 3°C	10.8-15.5
Long term load, 23°C	9.2-12.9
Short term load, 23°C	12.0-15.0

<table>
<tr><th>ULS</th><th>Range $f_{y,d}$ [N/mm^2]</th><td rowspan="5">To obtain these values, for the reduction factor on the welds the exemplary value A_S = 1.57 taken from Moritz [2] is used.

This value should be investigated by each manufacturer itself as it depends on the quality of their welds.

The 5% fractal value of the weld-strength should be derived based upon mono-axial tests.</td></tr>
<tr><td>Permanent load, 40°C</td><td>9.6-10.1</td></tr>
<tr><td>Long term load, 3°C</td><td>16.9-17.8</td></tr>
<tr><td>Long term load, 23°C</td><td>15.9-16.5</td></tr>
<tr><td>Short term load, 23°C</td><td>20.6-21.5</td></tr>
</table>

Table 10: Advised values for design stress for SLS and ULS

A5.4.8 Latest Developments at Dekra / Labor Blum [21]

The ideas that are formulating the basis of the plasticity theory are explained in a simplified manner: using a linear approximation instead of the 3-dimensional description. For the later use it will be necessary to be more precise. It can be stated that linear approximation will here be sufficient since elongations under biaxial loading do not exceed 6 -7 %, although they reach higher values in the case of uniaxial loading.

The yielding behaviour with hardening effect in a uniaxial tensile test shall be explained descriptively: an idealised stress-strain diagram is shown in figure 15. Idealising in this case means that all time-dependent viscous effects are neglected.

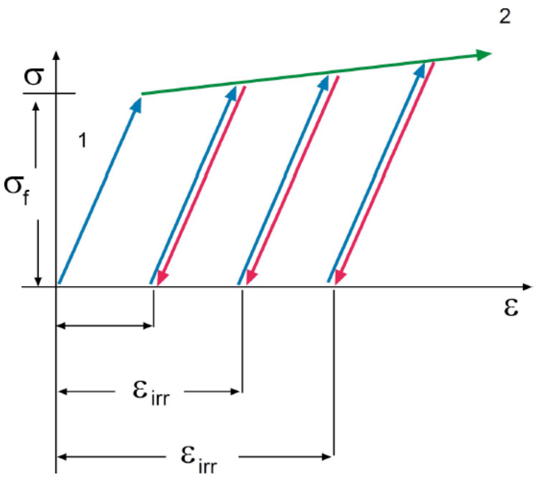


Figure 15, Idealised stress-strain curve

First the stress increases proportionally to the elongations like in an ideal elastic material (first blue line). After a certain stress value - the yield stress σf - the gradient becomes smaller, the increase of the stress decreases (green line). This part of the stress-strain curve is called the plastic branch. Unloading in this part results in a decrease of the stress parallel to the first increasing part (red lines). On reduction of the stress close to 0, an irreversible part of the strain ε_{irr} remains. Repeated loading will lead to an increase parallel to the first loading branch (blue lines). After having reached the plastic branch (green line) it will follow this one with the smaller gradient. Repeated unloading and loading leads to the same behaviour again and again. It seems that the actual yield stress increases after having exceeded the first yield stress. It can thus not be considered to be a material constant. This effect is called hardening. This behaviour can be described mathematically, and extended to the biaxial stress strain relation.

The yielding depends on the ratio of the two mean stresses. The theory of hardening may be developed from these simple considerations by assuming a non-constant quality k. The two-dimensional plasticity theory with hardening is actually being formulated. Not all test results have been analysed yet. A circular shaped sample of the biaxial testing machine of Dekra DII is shown in figure 16. The test machine has been converted to perform these tests. The stress field of this sample is more homogenous than the one of cruciform samples. The results are as such easier to interpret.

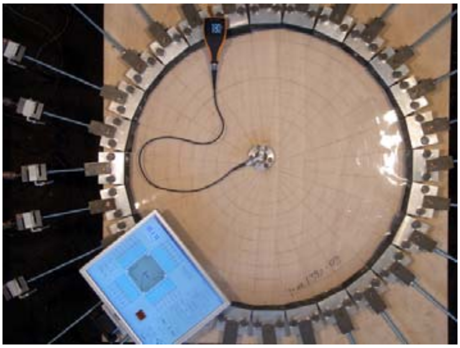


Figure 16, Multi-axial test on ETFE using a circular sample. In the middle the installation to measure the thickness.

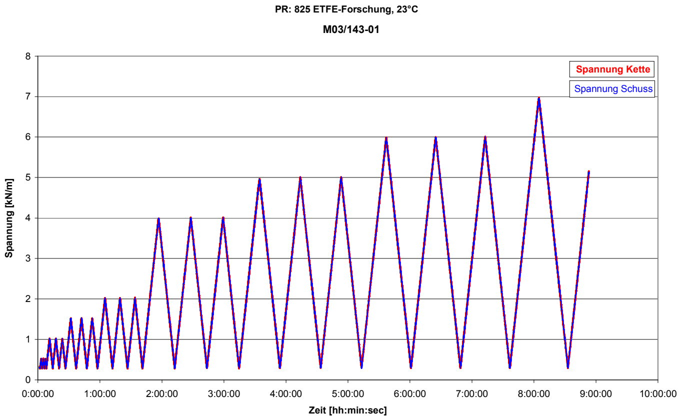


Figure 17, Load history for the tests performed with the circular sample, on the x-axis time [sec] and on the y-axis stress [kN/m]

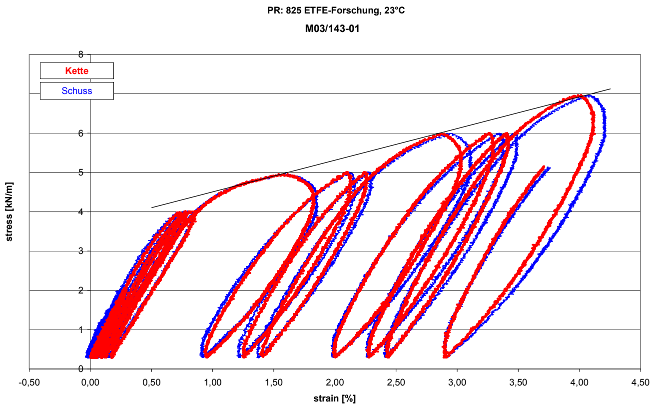


Figure 18, Deformation in direction of roll and perpendicular to roll direction. The interpretation of these results cannot be given here due to the lack of time. But it should be mentioned that the results conform to the von-Mises theory with hardening. It is to note that a viscous flow is superposed to the plastic behaviour. The yield point is not well defined.

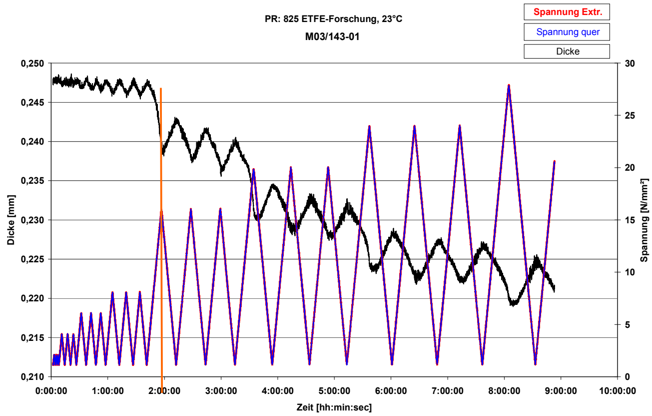


Figure 19, The behaviour of the thickness for this test with time [sec] on the x-axis and thickness [mm] on the y-axis. Here one can define clearly the yield point because of the step in thickness behaviour. This is marked with the orange line.

From these considerations the following points shall be taken into account for the design of ETFE structures:

1. The yield point is not a material constant. It depends on the load history. Thus it shall not be used for the design.
2. The yield point can be detected clearly if the change is measured during testing.
3. The first yield point depends using the yield criterion of von-Mises on the stress ratio of the two mean stresses. The yield point in the hardening branch depends on the ratio of the two mean stresses and the direction of the two axes of mean stress. Thus the mechanical behaviour after having reached the yield point in a uniaxial test is different from the behaviour in a biaxial test. As such the uniaxial failure criterion shall not be used for the biaxial failure. This behaviour can easily be explained: yielding under uniaxial tensile loading leads to an orientation of the molecular chains in the direction of stress. The negative elongation in the direction perpendicular is large. This can be described as yielding in the surface. In biaxial stress states the orientation cannot take place. As such yielding occurs in the third direction with a reduction in thickness.
4. After having reached the maximum stress and the loading is reduced, the yield area will be left, the material behaviour is elastic as long as the previous yield stress is not exceeded again.
5. After having exceeded the yield point, thus after hardening and unloading the elongation will not come back to 0. A residual strain will stay which is corresponding to the plastic part of the deformation. To this plastic deformation a viscous part is superposed which can be formulated by extending the plasticity theory with hardening effect by a viscous part.
6. The part, which is at the moment missing, is the biaxial criterion of failure. The common tests – biaxial tests in cruciform or circle shape fail at the edges and not on the centre of the sample. First results at Dekra/ Labor Blum show that a biaxial failure criterion will be found. Respective

tests are not finished yet. Therefore a new testing installation has been built in which the failure happens in the centre. Edge effects have not occurred.

7. The statical analysis of ETFE is expected to become clearer and easier using the presented method.
8. Recommending design procedures for ETFE at the moment means that they represent the actual state of knowledge and will be preliminary. A final recommendation for statical analysis and design can be defined after having evaluated all results and included into the material laws.

The full paper from Labor Blum / Dekra can be downloaded from the TensiNet website.

A5.5 Recommendation on modelling and analysis of ETFE cushions

To model the ETFE foil properly, it is the objective to stay within the linear range of the ETFE foil. However, depending on the load duration and temperature, the E-modulus of the material changes.
For reference see figure 7
Given values from [1] therefore are indicative and at 23°C:
Long term load E-modulus: $E_x = E_y = 405\ N/mm^2$
Short term load E-modulus: $E_x = E_y = 810\ N/mm^2$
Poissons ratio: 0.47
G-modulus: $276\ N/mm^2$
Given values in A5.5.1 are comparable (also 23°C):
$E_x = E_y = 900\ N/mm^2$
Poissons ratio = 0.33
G-modulus = $335\ N/mm^2$

A 5.5.1 Material properties and Analysis (form-TL)

As described above, the concept for the design is to stay in the linear range of the foil, so that the material properties can be taken as constant.
Based on biaxial tests we have determined that the given E-modulus is in the range of 900 N/mm², and with a Poisson's ratio of ν=0.33 all properties can be determined:

<u>Example values for 200 µm foil are:</u>
E_x= 180 kN/m, E_y= 180 kN/m, ν=0.33 and G= 67 kN/m

<u>Transformed to the direct stiffness:</u>
EAX= 200 kN/m, EAY= 200 kN/m, EAP= 67 kN/m and G= 67 kN/m.

Even though the material properties can be taken to be linear, the analysis must be performed assuming geometrically non-linear (large deflection) behaviour, and must include the buckling of the slack foil elements.
Furthermore, the shear stiffness of the foil is, compared to coated membrane, relatively high. Therefore it is recommended that this is incorporated in the analysis.

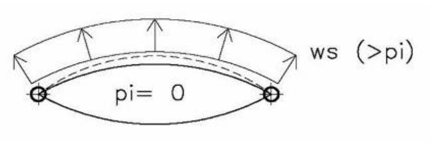
A 5.5.2 Constant volume (form TL)

The pressure in cushions interacts with the loads applied under short-term loading. Therefore, a constant volume analysis should be performed.
This means: p * V = constant (as for short-term loads temperature T can be assumed constant)
With p = the absolute value of the pressure in the cushion and V = cushion volume.

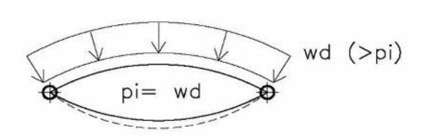
Some programs have included an option for this analysis, and adjust the pressure in the cushion iteratively, but even with a manual iteration this can be done within a reasonable time.

A 5.5.3 Constant volume simplified approach that can be used as well for small volumes (form-TL)

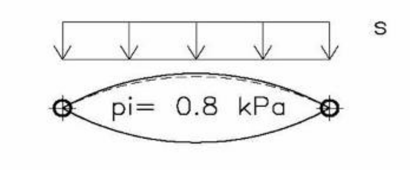
Case 1: Wind suction
Wind suction pulls the outer foil of the cushion towards the outside and tries to increase the volume. Because the air cannot follow and already a small change of volume, this leads to a complete loss of pressure in the cushion; the maximum wind suction acts on the outer foil of the cushion and the internal pressure becomes 0.
The upper foil layer carries the wind suction loads.
The lower foil layer is slack.



Case 2: Wind pressure
Wind pressure pushes the outer foil of the cushion towards the inner and, in the cushion, a balance with the wind load is set up. If the wind pressure is higher than the internal pressure, this results in an internal pressure equal to the wind pressure within the cushion.
The upper foil layer is slack.
The lower foil layer carries the wind pressure loads.



Case 3: Snow load, long term
In case of snow load the internal pressure is increased up to e.g. 800 Pa controlled by electric snow sensors. The internal pressure carries the snow load.



A5.5.4 Cutting pattern Generation

Generating cutting patterns for ETFE foil structures is similar to creating cutting patterns for anticlastic curved membrane structures. As the ETFE foil has a higher shear stiffness than fabrics, it is necessary to control the amount of distortion that is introduced in the patterns by the flattening process. If the distortion is too high, there will be wrinkles in the cushion.

Near the end of a cushion, there is normally a strong change in curvature. In this area it is easy to introduce too much distortion. A solution for this is to keep the cutting pattern width small at this area and prevent having anticlastic curvature in the corners of the cushion as this means a strong change in curvature for the foil.

In fact an air cushion is a small air hall. More information on cutting pattern generation of air halls can be found in the AIRHALL HANDBOOK (IL 15).

Figure 20, Too much distortion in the cutting pattern causes wrinkles in the cushions

A5.6 Structural design basis and safety criteria for single layer ETFE

A5.6.1 Recommendations by form TL on single layer ETFE foil

Single layer ETFE structures cannot compensate for the effects of creep, temperature and tolerances by a slight geometry change, as cushions do. Therefore, these effects must be taken into account during the design process.

Effect of the temperature (change in length):

The thermal expansion coefficient of ETFE is approximately 10×10^{-5}/K. The supplier Asahi Glass specifies for their material 9.4×10^{-5}/K, so more or less the same.

In central Europe the air temperature typically varies within a range between -20°C and +40°C. Assuming an installation temperature of 10°C we get a variation of +/-30 K, which results in a strain variation of **+/-30 x 10 x 1.0E-5 = 0.3%.**

Creep effect:

Under constant load, the ETFE foil creeps. The magnitude of the creep depends on the level of stress. In a uni-axial test, the material behaves as shown in the following graph (Asahi Glass).

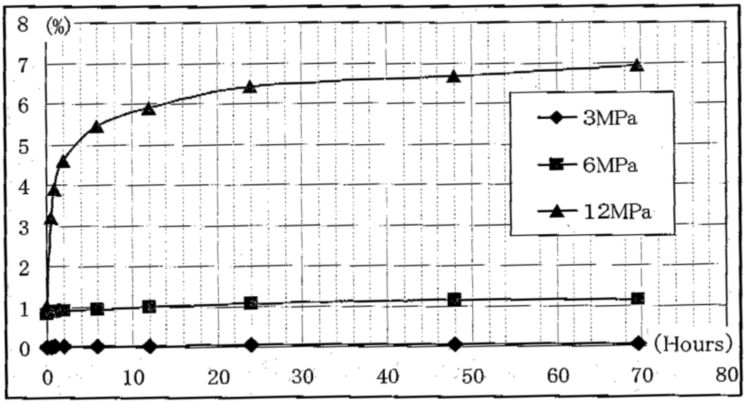


Figure 21, Creep diagram, AGC FLUON ET

This means that up to a stress of 3 N/mm² the impact of creep is negligible, and for a stress of 6 N/mm² it stabilises at approximately 1%. With a permanent stress of 12 N/mm² the material creeps uni-axially towards a value of 7 to 8% after 70 hours, but has still not stabilised.

In Biaxial tests it has been found that the biaxial strain is reduced to approximately 25% of the strain in uni-axial tests, so it is assumed that the permanent strain at 6 N/mm² will stabilise itself at a level of approximately 0.3 %, and at 12 N/mm² it will be approximately 2% after 70 hours.

This means ideally that the pretension in single layer ETFE foil structures should not exceed 3 N/mm² (e.g. 0.6 kN/m for 200 μm foil), and permanent high load like snow should be avoided.

The frequency and intensity of wind can only be determined statistically. In the following excerpt and graphs the wind speed in Germany is given in correlation with its probability.

As an example this distribution is applied in 5 steps, and the resulting intensity is determined relative to the design wind speed. For the yearly occurring wind the intensity is approximately 60% of the design wind pressure.

Statistical frequency and intensity of German wind speed				
Wind [m/s]	Wind per year	R (acc. to Caspar)	Wind load [kN/m^2]	Intensity [%]
45.5	0.03	30	1.3	100
40	0.2	5	1.0	77
35	1	1	0.8	59
30	5	0.2	0.6	43
25	29	0.035	0.4	30

Table 11: Statistical frequency and intensity of German wind speed

Based on this intensity the stress level is determined for a 200 µm foil in a recently realized example. Relevant for the strain in the foil is the stress acting in larger areas. Stress peaks are not taken into account for this.

200 µm Foil	Tension in N/mm^2				
Pretension	2.0				
Max tension under wind load	12.5				
	100%	77%	59%	43%	30%
Global tension under wind load	10.00	7.73	5.92	4.35	3.02

Table 12: Stress level of ETFE based on intensity level of Table 11

For the yearly wind the stress is approximately 6 N/mm², and under design load the stress can increase up to 12.5 N/mm².

For the biaxial tests appropriate load scenarios should be applied, in order to determine a realistic compensation factor, which takes into account a reasonable part of the permanent strain over the years.

Application

Once the short term compensation has been determined, these values must be corrected (if required) to comply with the strain variation due to temperature, and due to long-term creep.

In some cases it will be necessary to insert means for re-tensioning in the details, as shown in Figure 22, for example.

Compensation factors for ETFE are in the range of 0.2 to 0.6%. These low values don't allow for high tolerances, therefore it is highly recommended to apply adjustable details along the border. These details can be used as well for re-tensioning after some years.

Figure 22, Unilever Building, Hamburg (form TL)

A5.6.2 Recommendations by J.W.J. de Vries (TU Delft) on single layer ETFE foil

Jos de Vries has investigated mono-axial and biaxial properties of ETFE foil with the aim to define a design concept based on the "Limit State" approach. An important issue has been the determination of a yield point and creep limit. As the material behaves in a non-linear manner, a long- and short-term load is defined.

Reduction factors in Serviceability Limit State (SLS)

σ_d = $\sigma_{rep} / \gamma_m * k_{mod}$

σ_d = Design stress for ETFE foil

σ_{rep} = Representative stress for ETFE foil, to be determined (approximate values for 1:1; 12 N/mm^2, for 1:2 / 2:1; 15 N/mm^2)

γ_m = Safety factor for material uncertainties

k_{mod} = Modification factor for temperature and creep

γ_m = 1

Deformation criteria	Load duration	Temperature (°C)	k_{mod}
No permanent deformation	Less than 15 min	t < 20	0.84
		20 < t < 30	0.77
		30 < t < 50	0.60
	More than 15 min	t < 20	0.50
		20 < t < 30	0.46
		30 < t < 50	0.36

Table 13: Reduction factor k_{mod} depending on temperature and load duration, no permanent deformation

The focus of the research was on the Serviceability Limit State. It is assumed that the Ultimate limit State is not the restrictive state. Therefore no recommendations are mentioned for the ULS.
Important issues addressed here are the temperature dependence of the creep level and strength of the foil.

Maximum prestress level assumed at a temperature between 20°C and 30°C is

$\sigma_d = \sigma_{rep} / \gamma_m * k_{mod} = 12 / 1 \times 0.46 = 5.5 \text{ N/mm}^2$.

As the foil will get warmer than 30°C in summer, stresses should stay below to prevent creep.

$\sigma_d = \sigma_{rep} / \gamma_m * k_{mod} = 12 / 1 \times 0.36 = 4.3 \text{ N/mm}^2$.

A5.6.3 Comparison single-layer ETFE

To determine the appropriate values for the pretension level, different approaches can be taken: an approach not to allow for any creep or an approach for a controlled creep. It is anyway sure that the pretension level should be low compared to the possible pretension level of an ETFE cushion. The pretension level should range from 3 to 6 N/mm^2 depending on the anticipated elongation due to creep and the available adjustment possibilities. This is up to the judgement of the engineer.

A5.7 Manufacturing and Installation

A5.7.1 Material

ETFE is a thermoplastic fluoro-polymer and can be welded. ETFE-films are either transparent, transparent with printing, matted or pigmented (coloured). The typical film thicknesses for architectural application are in the range of 100 – 300 µm.
The melting point of ETFE is at 27° ± 10°C. ETFE has a high static loading, which does not affect its weldability but attracts dust to its surface and requires special care for safety of people in the workshop.

A5.7.2 Welding techniques

Due to its dielectric characteristics, ETFE cannot be high frequency welded. Hence ETFE-films are typically welded by using hot bar elements (i.e. thermal impulse welding or continuous welding). ETFE-film can also be welded by laser. Transparent ETFE-films let light pass at most laser frequencies which requires absorber layers for using excimer, N2, ND:YAG or diode lasers. ETFE-film absorbs more than 90 % of waves with wavelengths between 7400 to 10800 nm. Therefore CO_2 lasers can be used for welding.

Since all welding of thermoplastics is done under pressure, ETFE welding machines need to be adjusted with precision to avoid excessive squeezing of melted ETFE-film.

ETFE-films shall be processed on clean surfaces to avoid scratches on the surfaces and accumulation of dirt and dust due to the static loading of the material. In order to reduce static loading, films shall not be pulled over the ground or table surfaces.

Dust and perspiration and oil from skin reduce the welding seam strength. Workers should wear gloves to avoid finger prints on the film. Stained film shall be cleaned before welding by using appropriate cleaning liquids according to the film manufacturers' recommendations.

When fritted foils are to be welded, it shall be proven by testing that printing does not affect the tensile strength of the welded seam. It is recommended to remove printing in the seam area by using appropriate solvents. Care shall be taken to make sure that smallest, probably invisible to the eye, printing colour pigment stains are removed before welding.

ETFE-films shall be handled with care to avoid sharp folds or kinks, which may become visible in light passing through after installation.

A5.7.3 Welding seam strength and testing

Welding seam strength shall be tested at 23°C and 50°C from the material batches which are used in the project. If printed foil is being used, welding seam strength tests shall be performed using material batches with fritting by using the same welding and print removing techniques as are being used during production.

Evaluation of a number of tests shows, that foil stresses at break are
≥ 30 MPa at 23°C
≥ 25 MPa at 50°C

The values are given as an indication to assess the quality of a weld. In order to assess the welding of a specific project, the required seam strength shall be derived from the statical calculation of the project.
Testing shall include testing of the Keder edge detail at 23°C and 50°C. The minimum seam strength requirements deriving from the cushion analysis shall be used for evaluating the quality of the seams.

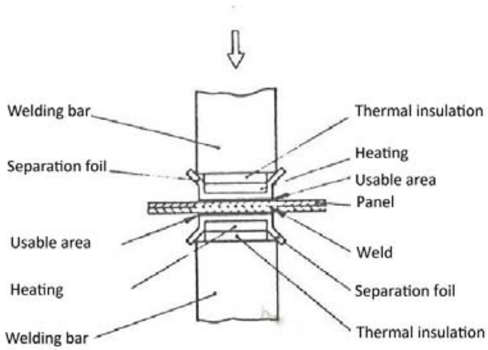


Figure 23, Principle of thermal impulse welding

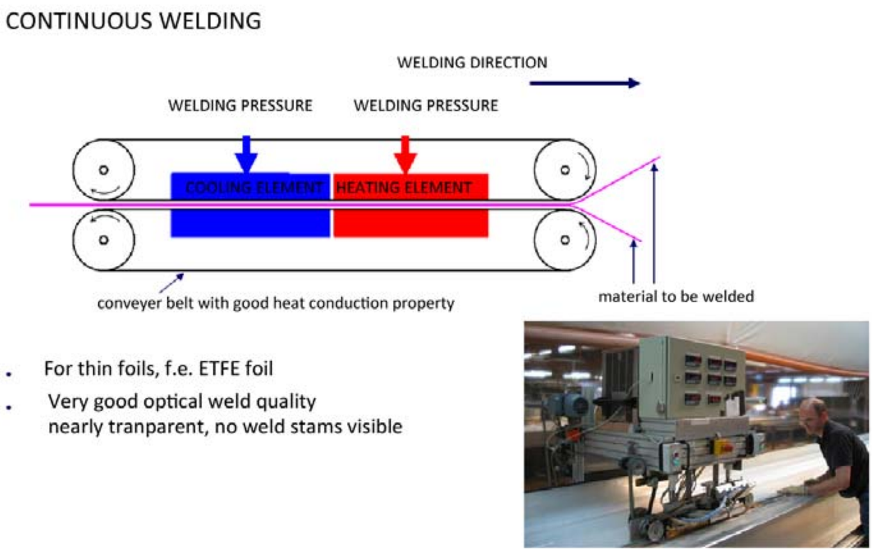


Figure 24, Principle of continuously working thermal impulse welding (release belt made of PTFE coated fabric)

Figure 25, Failure of the weld

When welding printed foil, special care should be taken to clean the welding area. The picture above shows failure of the weld after some time since the print was not removed before welding.

A5.7.4 Packing

Packing shall be done with care to avoid sharp folds or kinks. The folding plan shall be established with the installation team and shall include packing instructions. In order to avoid damage and staining during transport and storage stable wooden crates with plastic liners should be used for packing. Each packing unit shall have clear marks and packing instructions visible on its outside surface along with marking on the foil itself which identifies the position of the foil clearly for the installation staff.

A5.7.5 Installation

For installation purposes, it is possible to use life-nets as a temporary platform for installation. The air supply units should be installed and functioning prior to the installation of the cushions. When one cushion is installed, the air supply should be connected as soon as possible. When there is danger of a wind gust, the non-inflated cushion needs to be secured temporarily. Wind gust on a non-inflated cushion might damage the cushion or endanger installers.

Special care should be taken that no other parties at the building site might damage the cushions.

Special care should be taken for a continuous power supply during the building process. It easily happens that the power supply is turned off outside normal working hours. Consequently, the cushions will then deflate.

A5.7.6 Recommendations on Air inflation system & control

Figure 26, Internal inflation unit, Stainless Steel piping Figure 27, External inflation unit

ETFE cushion systems are permanently inflated by air inflation units located close to the cushions. As the cushions only need to maintain pressure and not generate air flow, their energy consumption is minimal. An entire roof is generally powered by 2 or more fans powered by electric motors within each inflation unit (1000 m^2 per unit). The fans are normally used alternately and intermittently to maintain pressure with only one fan running at any given time and typically consume less than 100W when in operation. In the event of a cushion failure, both fans will be used to maintain a steady pressure.

A typical air inflation unit measures 1.2m x 1.2m x 0.9m and is located nearby to the ETFE cushion system, internally or externally. The system requires a dedicated and secure power supply. As the ETFE foil roof is a live system, the cushions are permanently linked to the air inflation unit to ensure the pressure is maintained. The inflation units are fitted with dehumidifiers as standard to dry the air being fed into the cushions.

A5.7.6.1 Power failure

In the unlikely case of a power failure, the ETFE cushion system will maintain its pressure for between 3 and 6 hours before deflating (dependant on weather conditions). This is due to the non-return valves built into the air inflation units. After this time, there is a possibility that the roof will become damaged. Therefore, it is recommended that there is either a standby generator or alternatively a cable bracing system installed to support the cushions in this situation. In addition, it is advisable that the roof is closely monitored to avoid these problems occurring.

A5.7.6.2 Monitoring of inflation units

It is recommended that the building monitoring system is also connected to the air inflation units. When there is an error in the inflation unit, it will be seen directly and action can be taken. Also the level of pressure in the cushions should be monitored. When there is an adaptive air pressure system that raises the pressure to resist high wind or snow load, there is potentially the risk that the inner

pressure may raise without the compensating load (e.g. snow load) being present. This can be dangerous especially in summer time, where a high internal pressure combined with higher temperatures will lead to large permanent deformation.
Inner pressure may be used to compensate the maximum snow load, but other solutions should be investigated at first. If exceptional loads and damages can be avoided structurally, e.g. avoiding water ponding by roof inclination or drainage, the risk of too high pressure without need is prevented. However, ponding under snow (exceptional loads) have to be considered in static analyses. On the other hand it is known that snow load assumptions based on codes are higher than snow loads on ETFE-cushions in reality (mostly).

A5.7.6.3 Quality

As the life expectancy of ETFE foil is high, care shall be taken in choosing materials for the air supply. To show the effects of neglecting the lifespan of the connecting materials, a few pictures are shown:

Figure 28 and 29, Clamped flexible PVC hose, broken
Figure 30, Glued hard and soft PVC, will be damaged by UV light, elongation

The choice of materials that are not UV-resistant will lead within a few years to cracks and broken parts. Even if the material is not subjected to direct sunlight, in time the material will become brittle and possibly break.

A5.8 Performance, Durability and Maintenance

A5.8.1 Thermal behavior of ETFE cushions

Although ETFE foil structures already have been built for more than 30 years, it remains a specialist product. Its performance, durability and maintenance are strongly influenced by the way the connection detailing is solved and how for example the air supply is addressed. Even more important is the way the internal environment is regarded during the design process. As with all structures, a good functioning structure starts with a proper design.

ETFE foil is stated as being a highly transparent material. In the graph of figure 31 it can be seen that the visible light is transmitted abundantly through ETFE, one of the reasons why it is used. It also transmits UV light to a greater extent than glass which is beneficial for solaria and swimming pools as it assists tanning, and also for greenhouses, where the bactericidal and fungicidal properties of UV light reduce the need for pesticides and fungicides [19].

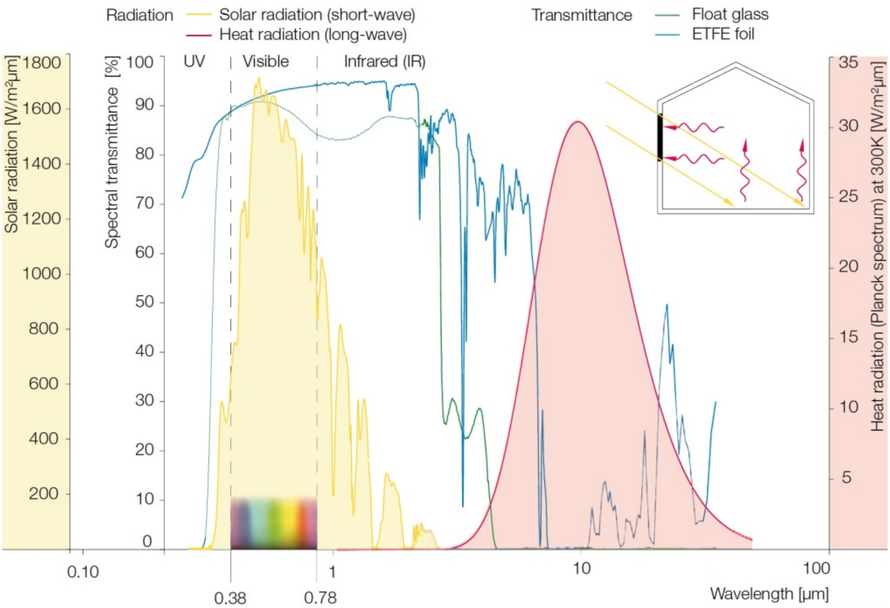


Figure 31,: Correlation of greenhouse effect [18], picture by Jan Cremers

Each object with a temperature higher than 0°K radiates. When the temperature of the object is higher, the wavelength of the radiation frequency becomes smaller. The radiation that the object receives, can be reflected, absorbed or transmitted.

Sunlight that enters a building is short wave radiation. Both glass and ETFE transmit and absorb short wave radiation. The object below the glass or ETFE (the floor) that receives this light absorbs the solar radiation which leads to an increase of its body temperature. The increase in temperature causes emission of long wave radiation (far IR). As Glass and ETFE do not transmit this long wave radiation, the radiated energy stays inside the building. This is the so-called greenhouse effect. The interior

space is heated up by the sunlight. Contrary to glass, ETFE foil partially transmits long wave radiation, which may cause a slightly difference. As the peak in emissivity of the objects below the surface is around 10 to 20µm, this cannot be seen as a governing transmission effect (figure 31).
The light transmission can be reduced by a frit pattern applied to the ETFE foil surface. These frit patterns can vary both in ink translucency and printing density. Even the number of fritted layers of foil can be used to control the entrance of light.

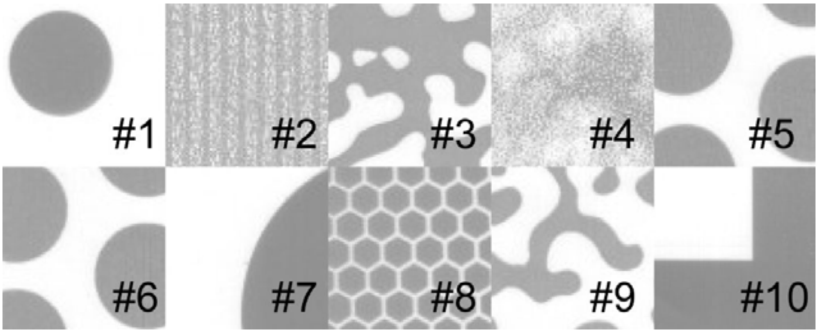


Figure 32, Scanned examples of different frit patterns; relates to Table 14[16]

Frit Ref #	Description	Ink Trans %	Coverage %	Trans %
n/a	Clear 200µ ETFE	n/a	0	87
1	Large dots	23	20	74.2
2	Static lines	28	30	69.3
3	Camo	23	35	64.6
4	Clouds	32	46	61.7
5	Med dots	32	50	59.5
6	Med dots	23	50	55
7	Large dots	23	62	47.32
8	Hex	28	70	45.7
9	Inverse Camo	23	70	42.2
10	Chequered	23	75	39

Table 14: Estimated visible light transmissions (Trans %) calculated from manufacturer's ETFE datasheets [16]

Overheating might occur when no proper care is taken to manage the greenhouse effect. Compared to glass, ETFE has a higher translucency over a wider wavelength range. It, therefore, is not possible to use U-values based on double glazing although they seem to be rather comparable:

	U-value (W/m^2K)	g-value
6mm monolithic glass	5.9	0.95
6-12-6 Double Glazing Unit (DGU)	2.8	0.83
6-12-6 High Performance DGU	1.2 **	0.35
2 Layer ETFE Cushion	2.9 (3) *	0.71- 0.22 (with frit) (0.85 no frit) *
3 Layer ETFE Cushion	1.9 (2) *	0.71- 0.22 (with frit) (0.80 no frit) *
4 Layer ETFE Cushion	1.4	0.71- 0.22 (with frit)

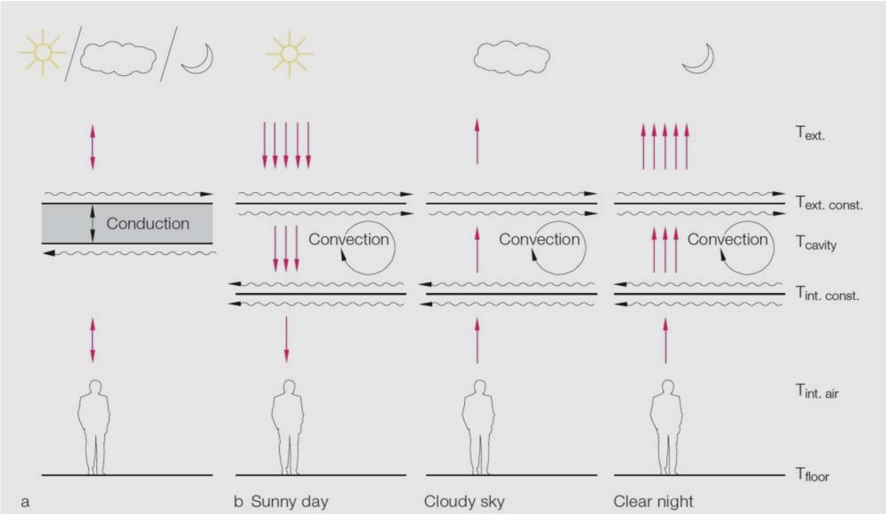
* values as cited in [18, figure E 5.13], ** value as cited in [17]

Table 15: Seeming correlation between Glass and ETFE cushion thermal / solar data as cited in [16].

The U-values approach is developed for massive structures where conduction predominates and takes into account a limited temperature difference. For thin multi-layered and small mass structures, radiation and convection are much more significant.

As opposed to glass double glazing units where argon or krypton in the cavities reduces the heat exchange due to reduced gas conductivity and a low-emissivity coating on one of the panes reduces the long wave radiation exchange and thereby reduces the thermal transmittance of the system, ETFE cushions have normal air in large cavities of varying depth and do not have low-emissivity coatings commercially available. This leaves the key effects to be considered; the emissivity of the cushions and the convection.

Especially when there it is a clear night sky or a hot summer day this will cause a strong energy transport by radiation. Surfaces exposed to this energy transfer can cool down or heat up considerably. Therefore the direction of the energy transfer should be taken into account while evaluating the energetic performance of the building [18].



a) Typical opaque design with mass or thermal insulation

b) Radiation-permeable design with separate layers and low mass [18, figure E 5.6], picture by Jan Cremers

Figure 33, How radiation-permeable designs are dependent on the weather

A5.8.2 Glare & Noise levels

Table 14 and figure 32 display different frit patterns. These are only examples of some of the available frit patterns; it is up to the creativity of the designer to develop alternatives. The effect of the fritting can be estimated based on the available data. But the actual g-value of a frit pattern can only be determined by testing. With a test, also the effect of the changing angle of the sun can be taken into account. Overestimation of the g-value causes internal glare and overheating.

Due to the taut drum-like nature of tensioned single-layer ETFE and inflated ETFE cushions, in heavy rain there is a chance that a level of noise is reached that could be considered unacceptable in occupied areas under the cushion array. This may be addressed with the application of an external mesh layer stretched over the ETFE cushions to break up a proportion of the larger raindrops, to dampen their impact, and to dampen vibration of the outer layer of the cushion. Installation of an external mesh also reduces glare and benefits the thermal performance, by absorbing solar energy and decreasing the g-value, resulting in an effective multi-purpose barrier.

A5.8.3 Fire behaviour

ETFE foil is considered to be self-extinguishing as it has low flammability (270°C). It does not burn, but does shrink away at higher temperatures. Due to the very low self-weight, the material disperses and does not cause molten drips. The melting and shrinking of the foil causes a beneficial effect for smoke exhaust. This can be accepted by authorities as being the only smoke exhaust system. Several fire certificates are available:

DIN 4102 Class B1
EN 13501-1 Class B-s1,d0
NFP 92-505 M2
NFPA 701 Pass

The actual Fire test certificates are to be supplied by the foil manufacturer.

A5.9 Literature

[1] De Vries, J.W.J., Tensile Foil, Dissertation, TU Delft, 2003

[2] Moritz, Karsten, ETFE-Folie als Tragelement; Dissertation, TU Munchen, 2007

[3] Stimpfle, Bernd, Tensinet ETFE, FormTL, Radolfzell, 2009

[4] Architen Landrell, ETFE foil - A Guide to Design

[5] Boegner, Heidrun, ETFE Comments, Labor Blum, Stuttgart

[6] Schiemann, Lars, Tragverhalten von ETFE-Folien unter biaxialer Beanspruchung, Dissertation, TU Munchen, 2009

[7] Stimpfle, Bernd, Tensinet, Single Layer ETFE, Rodolfzell, 2010

[8] Pöhling, Thomas, ETFE Welding, Cenotech, Greven, 2010

[9] Galliot, Cedric, Luchsinger, Rolf, Uni-axial and biaxial mechanical properties of ETFE foils, Polymer Testing, Volume 30 Nr. 1/2011, Page 356–365 ISSN0142-9418 Elsevier, 2011

[10] Wu, M., Lu, J., Experimental Studies on ETFE cushion model, Proceedings of the IASS Symposium, Mexico, 2008

[11] Blum, Rainer, Boegner, Heidrun, Némoz, G., Testing Methods and Standards, in: Forster, B., Mollaert, M. (Eds.), TensiNet, European Design Guide for Tensile Surface Structures, pp. 293–322., 2004

[12] Lucas, Jörg, Krombholz, A., Petersilge, M., Schäuble, R., Heilmann, A., Johlke, S., Trogies, E., Material Properties and Mechanical Behaviour of pneumatically stabilized ETFE Membrane Cushions, VDI Berichte, Page 269–274 (1970), 2007

[13] Kawabata, M., Moriyama, F., Study on Viscoelastic Characteristics and Structural Response of Film Membrane Structures, Proceedings of the IASS Symposium, Beijing, 2006

[14] Kawabata, M., Viscoplastic Properties of ETFE Film and Structural Behavior of Film Cushion Proceedings of the IASS Symposium, Venice, 2007

[15] Xiang, Y. Li, J., Calculation and Design of ETFE Membrane Structures, Proceedings of the IASS Symposium, Beijing, 2006

[16] Ward, J., Chilton, J., Heslop, A., Rowell, L.: Internal environment in ETFE foil covered building enclosures, Tensinet Symposium Sofia 2010

[17] HOAR, C., The future of Glass in Buildings, Saint Gobain Solaglass

[18] Knippers, J., Cremers, J., Gabler, M., Lienhard, J.: Construction Manual for Polymers + Membranes Paperback, Detail 2011

[19] LECUYER, A., ETFE : Technology and Design, Birkhauser, Basel, 2008

[20] SAXE, K., Zur Berechnung und Bemessung von ETFE-Folientragwerke, Essener Membranbau Symposium 2012

[21] Blum, R., Bögner-Balz, H., Könnlein, J., Lineair E- and P- theory, Labor Blum (Dekra), 2013

A5.10 Relevant Literature

1 Knippers, J., Cremers, J., Gabler, M., Lienhard, J.: Construction Manual for Polymers + Membranes Paperback, Detail 2011

2 Stimpfle, B., Unilever façade Hamburg, Germany, Job report, Tensinet Symposium Sofia 2010

3 Houtman, R., ETFE Roof JinSo Pavilion, Tensinet Sympsoium Sofia 2010

4 Schmid, G., ETFE cushions and their Thermal and Climatic Behaviour, Tensinet Symposium Milan 2007

5 Rudorf-Witrin, W., ETFE-Foil: a New Material for Textile Architecture, Tensinet Symposium Milan 2007

6 Moritz, K., The single layer-ETFE-Cladding for the National Stadium in Beijing, Tensinet Symposium Milan 2007

7 Schiemann, L., Moritz, K., Polymer Foils used in Construction, Chapter 6 in: Pohl, G. (Ed.) Textiles, Polymers and Composites for Buildings, Woodhead Publishing Series in Textiles, Cambridge, UK, 2010

8 Moritz, K., Hafner, A., Transparency carried by Air – Pneumatic ETFE-Foilcushion-Technology, Proceedings of the conference NASCC, Orlando, USA, 2010

9 Moritz, K., Time-Temperature-Shift (TTS) of ETFE-Foils, International Conference on Textile Composites and Inflatable Structures, Structural Membranes, Stuttgart, 2009

A5.11 Picture Credits

Figure 1	DyneonTM Fluorothermoplastics, APD 2010 Technical Training; S. Zehentmaier, Dyneon GmbH
Figure 2	http://www.agc.com/english/chemicals/jushi/etfe/etfe.htm
Figure 3	J. Nentwig, Kunststoff-Folien – Herstellung – Eigenschaften – Anwendung, 2. Auflage, Carl Hanser Verlag, München, 2000
Figure 4	J. Nentwig, Kunststoff-Folien – Herstellung – Eigenschaften – Anwendung, 2. Auflage,Carl Hanser Verlag, München, 2000
Figure 5	DyneonTM Fluorothermoplastics, APD 2010 Technical Training; S. Zehentmaier, Dyneon GmbH
Figure 6	Hostaflon ET 6235, Hoechst Broschure, 1983
Figure 7	DyneonTM Fluorothermoplastics APD 2010 Technical Training; S. Zehentmaier, Dyneon GmbH
Figure 8	Picture by Buitink Technology
Figure 9	Picture by seele cover GmbH
Figure 10	Galliot, Cedric, Luchsinger, Ralf, Uni-axial and biaxial mechanical properties of ETFE foils, Polymer Testing, Volume 30 Nr. 1/2011, Page 356–365 ISSN0142-9418 Elsevier, 2011
Figure 11	Galliot, Cedric, Luchsinger, Ralf, Uni-axial and biaxial mechanical properties of ETFE foils, Polymer Testing, Volume 30 Nr. 1/2011, Page 356–365 ISSN0142-9418 Elsevier, 2011
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Figure 21	Creep-Diagramm, AGC, FLUON ET, AGC Brochure
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Figure 23	Krist, Th., Schweißen Schneiden, Löten, Kleben, S. 515, Darmstadt, 1985
Figure 24	Gipperich, K., CENO TEC GmbH, Greven
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Figure 29	Picture by Tentech
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Figure 31	Picture by Jan Cremers
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Figure 33	Picture by Jan Cremers

Content

ETFE Working Group TensiNet

TensiNet ETFE Working Group
Markus Balz, Matthew Birchall, Rainer Blum, Heidrun Bögner-Balz, John Chilton, Jan Cremers, Helmut Frisch, Cedric Galliot, Klaus Gipperich, Rogier Houtman, Jochen Köhnlein, Karsten Moritz, Bernd Stimpfle, James Ward and Sebastian Zehentmaier
Chaired and edited by Rogier Houtman

The *Design Recommendations for ETFE foil Structures* are a product of over 4 years work by TensiNet ETFE Working group. TensiNet is an association or platform for all parties interested in tensioned membrane structures. It is a multi-disciplinary association, conforming to the initial objectives of the EU-funded thematic network (2001-2004).

The Design recommendations for ETFE foil structures have been established as a separate Annex of the European Design Guide for Tensile Surface Structures, published by the TensiNet Association in 2004.

Although ETFE is a widely used material, it is still a young material compared to other materials as steel, wood and concrete. A European standard is not available nor is extensive research on mechanical properties. These design recommendations present current knowledge and compare different design concepts. Therewith it is a 'state-of-the-art' report, not intending to be comprehensive. However, as TensiNet is involved in the preparation of a Eurocode on Membrane Structures (CEN/TC250 WG5), these recommendations will be used as input for the Eurocode on Membrane Structures.

This Guide recommends safety requirements which need to be considered for the design, calculation, manufacture, installation, maintenance, operation, examination and testing of ETFE foil structures. This can be applied to double- and multi-layer ETFE cushion structures or single layer tensioned ETFE membrane structures.

The field of application of this Guide includes all kinds of ETFE covered structures. The content of this Guide brings together the different existing concepts as far as possible.

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