Design Recommendations

Designing Air inflated Structures

Structural Design of Air Cushions

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contact: k.moritz@taiyo-europe.com

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AMA – architectural membrane association e.V.
c/o Anhalt University of Applied Science
Seminarplatz 2a
06846 Dessau – Germany

Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

1.0 Purpose

These design recommendations refer to aspects of the structural design of pneumatically pre-stressed structures, especially air inflated cushions made of ETFE-foils.

Up to now, no material-specific Eurocode exists for textile membranes and for ETFE-foils, used in building structures. A material- and structure-specific Eurocode for membrane structures is planned and in progress, but it will still need a few years until the first draft is published. Until the launching of this Eurocode, the structural engineer is required to apply the current state of the art, which is given by the document ”Prospect for European Guidance for the structural design of Tensile Membrane Structures”, that has been published by the European commission in the year 2016. In that document different approaches for the structural design of ETFE-foil structures are to find.

Furthermore, all relevant and actual local standards and codes are to consider. This is valid in the sphere of the Eurocode too. Here, especially the parts of DIN EN 1990 and DIN EN 1991 are to consider.

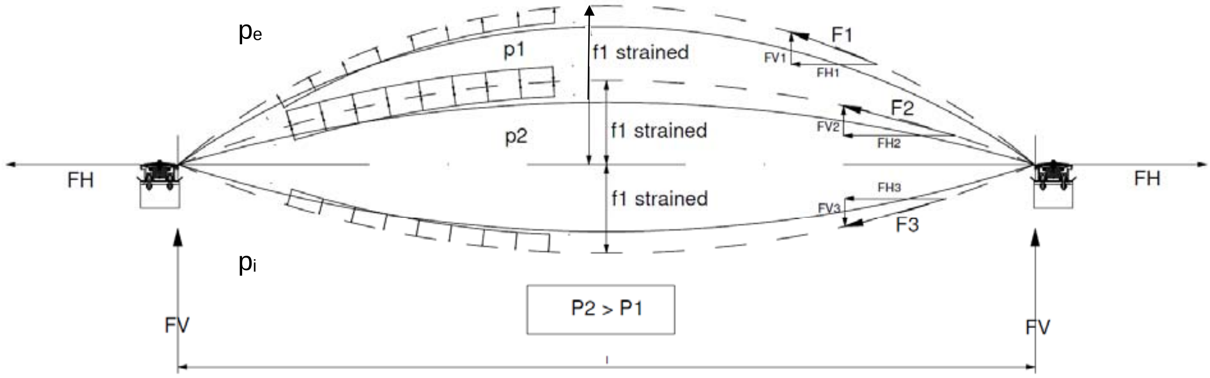
This document focus on the explanation of the structural design approach, given in the chapters 7.3.4 (SLS) and 6.4.3 (ULS) of the above-mentioned document (see attachment). The approach (for SLS and ULS) was also published in the year 2013 already (see “Annex A5 of the TensiNet European Design Guide for Tensile Structures, chapter A5.4.4). The approach was developed by MORITZ, based on materiel tests on ETFE-foils, published in his dissertation from the year 2007 [2].

The document in hands delivers explanations referring to the partial safety factors (γ_m, γ_L), reduction factors (A-factors, especially A_3) and load cases (LC), applied in the above-mentioned approach. If necessary, the document will be supplemented successively.

AMA – architectural membrane association e.V.
c/o Anhalt University of Applied Science
Seminarplatz 2a
06846 Dessau – Germany

Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

2.0 Principal load bearing behavior of ETFE-foil cushions



actio: |Σ FH| = FH1 + FH2 + FH3 = reactio |FH|
actio: |Σ FV| = FV1 + FV2 - FV3 = reactio |FV| = 0

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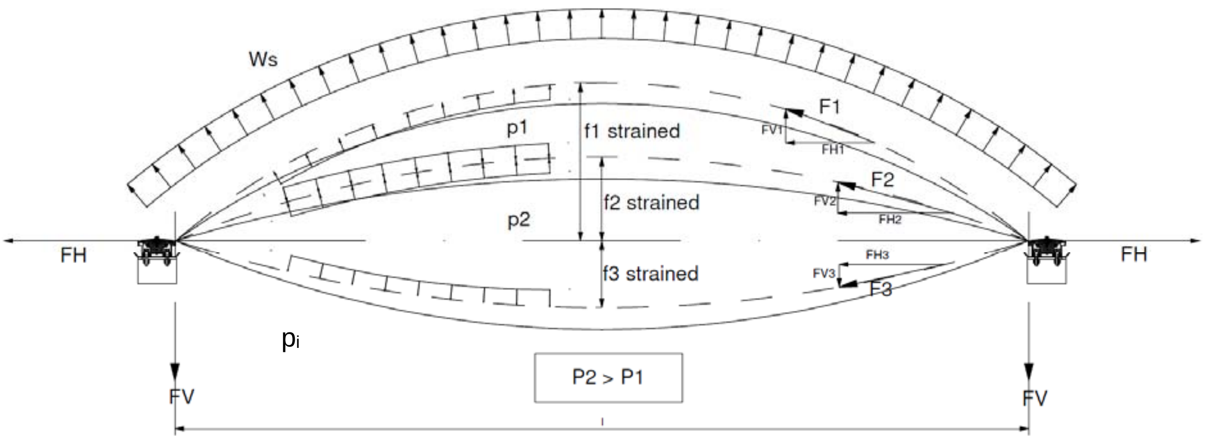
Fig. 1 Principle of the uniaxial load bearing behavior of a pneumatic cushion (here: 3-layer system) - load case pre-stress (internal pressures p_1 and p_2) [1]



actio: |Σ FH| = FH1 + FH2 + FH3 = reactio |FH|
actio: |Σ FV| = FV1 + FV2 - FV3 = reactio |FV| = Ws,v * l * 0.5

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Fig. 2 Principle of the uniaxial load bearing behavior of a pneumatic cushion (here: 3-layer system) - load case wind suction Ws [1]

AMA – architectural membrane association e.V.
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Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
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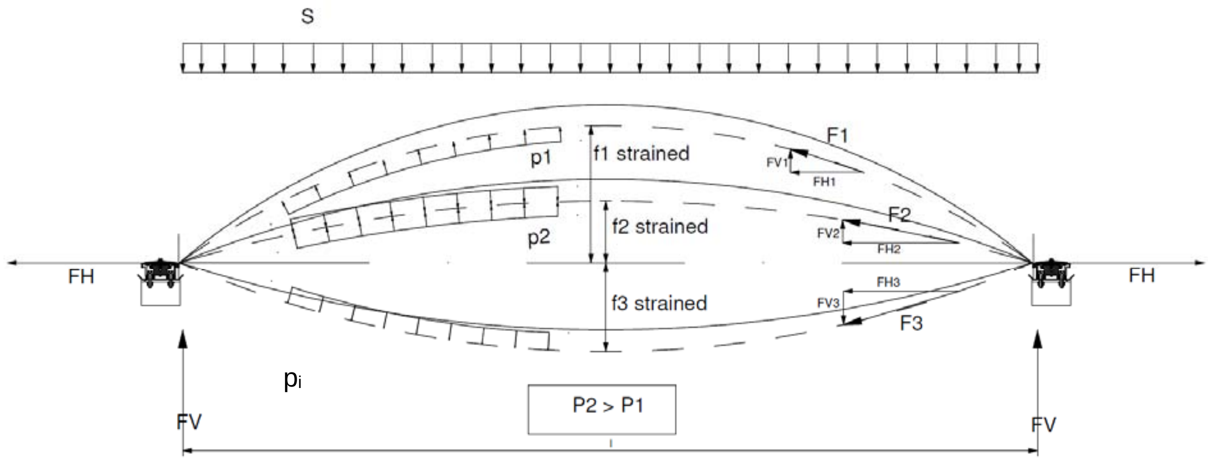
www.ama-forum.com



actio: |Σ FH| = FH1 + FH2 + FH3 = reactio |FH|
actio: |Σ FV| = FV1 + FV2 - FV3 = reactio |FV| = S * l * 0.5

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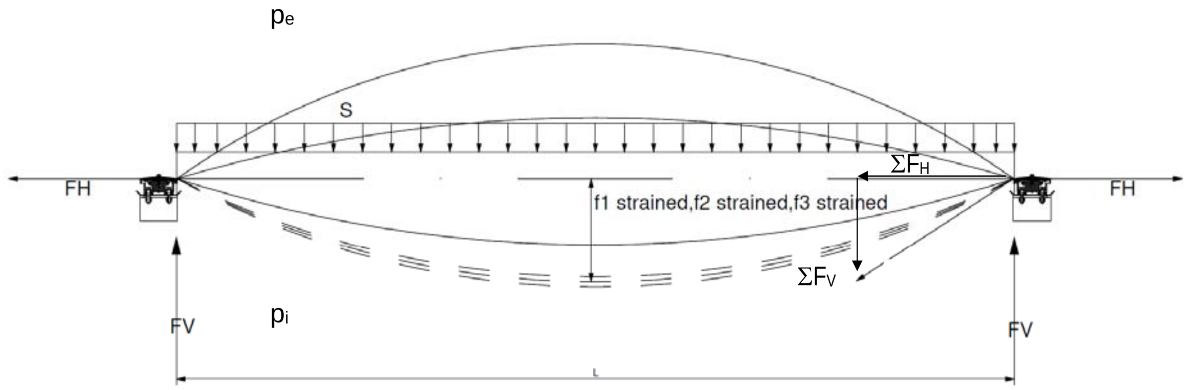
Fig. 3 Principle of the uniaxial load bearing behavior of a pneumatic cushion (here: 3-layer system) - load case uniform snow S [1]



actio: |Σ FH| = FH1 + FH2 + FH3 = reactio |FH|
actio: |Σ FV| = FV1 + FV2 + FV3 = reactio |FV| = S * l * 0.5

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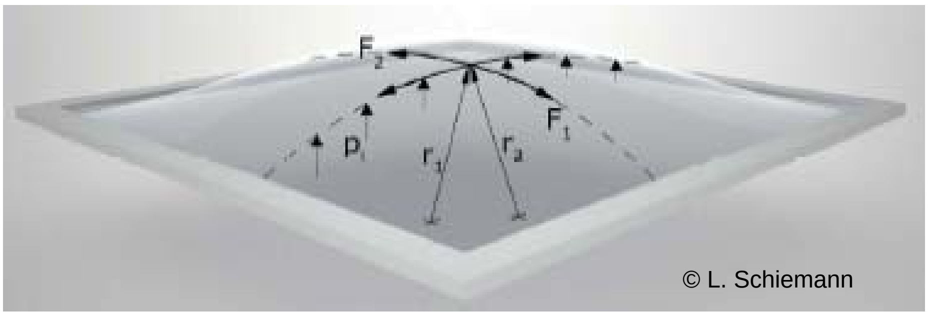
Fig. 4 Principle of the uniaxial load bearing behavior of a pneumatic cushion (here: 3-layer system) - load case uniform snow S on a deflated cushion or if the snow load S exceeds the internal pressure in the cushion [1]



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06846 Dessau – Germany

Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

Fig. 5 Internal pressure p_1, principal forces F_1, F_2 and principal radii r_1, r_2 in the outer layer of a square cushion (simplified) [3]

3.0 Structural Analyses – Serviceability Limit State (SLS)

3.1. Design resistances in SLS

$f_{d,SLS} \leq f_{R,d,SLS}$ with the design value of the resistance in SLS: $f_{R,d,SLS}$

3.1.1. Reduction factors (A-factors) in SLS

Table 7-3 A-factor values for the SLS verification

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

* 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-dependency of A_3 is given by Figure 2.27 in [Mor07].

Fig. 6 Applied reduction factors (A3-factors), ref. to [4], [5]

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3.1.2. Reduction factor A3

The reduction factor A3 for consideration of the temperature influence on the characteristic stress limits in SLS is taken from the following diagram.

The shown graphs are basing on the evaluation of uniaxial tests on ETFE-foils (NOWOFLON ET6235Z) according to DIN 527-3 [2]:

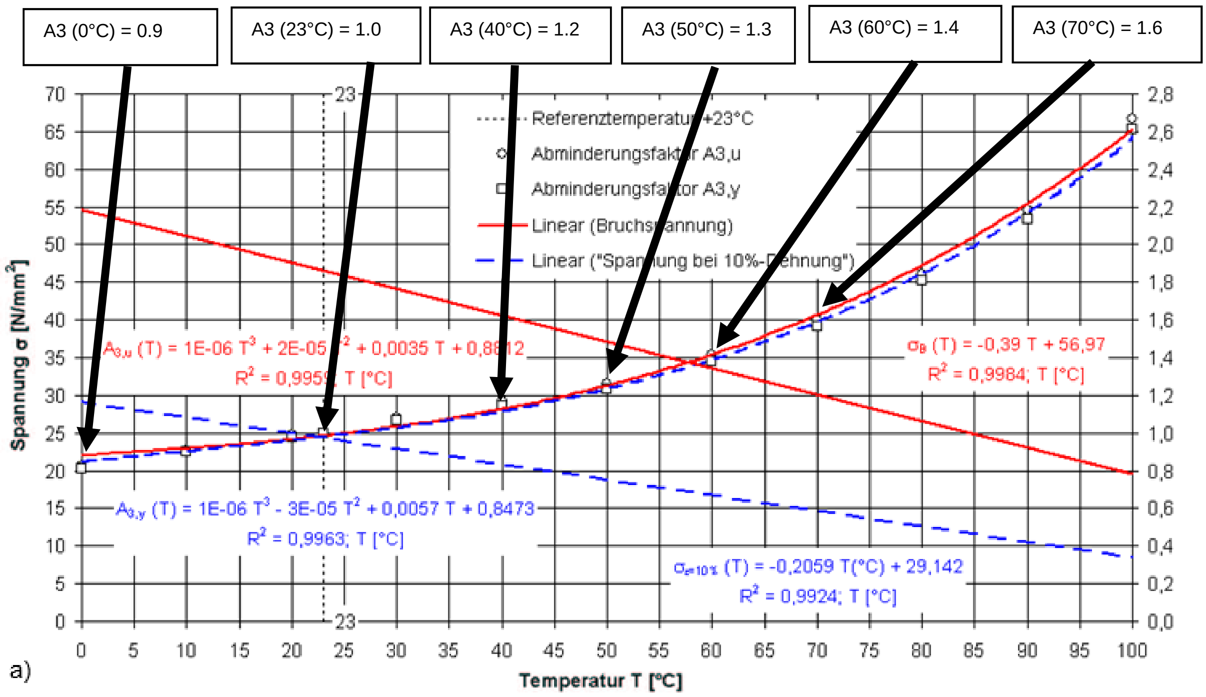

Fig. 7 Reduction factors (A3-factors); rounded up values for consideration of the influence of the temperature on the uniaxial tensile strength (ULS-limit) and on the stress at 10% strain (close to the 2nd yield point, that is considered as characteristic SLS-limit), ref. to [2]

3.1.3. Characteristic value of the Stress Limits in SLS

Table 7-4 5%-fractile values of mono-axial yield strengths of ETFE foil (material and weld) at T = 23°C and T = 3°C [Mor07]

Temperature / Vlaue	5%-fractile values of mono-axial yield strength (2. yieldpoint) of ETFE-Foil
T=23°C	$f_{y,k,0.05,+23°C}$ = 21 N /mm²
T=3°C	$f_{y,k,0.05,+3°C}$ = 25 N /mm²

Fig. 8 Applied characteristic values of the Stress Limits in SLS, ref. to [4], [5]

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3.1.4. Partial Safety factor (γ_m) in SLS

Table 7-5 γm for SLS verification

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

Fig. 9 Applied partial safety factor on the resistance (material) side in SLS, ref. to [4], [5]

3.1.5. Design values of stress limits in SLS

$$R_{d,SN,SLS,W_S} = \frac{f_{y,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1.0 \cdot 1.4 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0} = 15.00\ N/mm^2$$

$$R_{d,SN,SLS,S} = \frac{f_{y,k,F,0.05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{25}{1.0 \cdot 1.4 \cdot 1.3 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0} = 13.73\ N/mm^2$$

$$R_{d,SN,SLS,p_{nom}} = \frac{f_{y,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{21}{1.0 \cdot 1.4 \cdot 1.8 \cdot 1.0 \cdot 1.2 \cdot 1.0 \cdot 1.0} = 6.94\ N/mm^2$$

with

w_S wind suction,

S snow,

p_{nom} inner pressure.

The resistances R_d shall be compared and be larger than the design load F_d: $R_d > F_d$.

Fig. 10 Equations for the design values of the resistances in SLS – shown exemplary for three load cases, ref. to [4], [5]; Finally, adequate equations (proofs) have to be analyzed for all relevant load cases and for each load bearing layer.

Note: The exemplary equations, shown in figure 10, are basing on the following applied temperatures:

Wind suction, applied on layer 1 (upper layer): T = + 23°C ($f_{y,k,0.05,\,+23°C}$ = 21 MPa, A_3 = 1.0)

Snow load applied on layer 2 (lower layer): T = +3°C ($f_{y,k,0.05,\,+3°C}$ = 25 MPa, A_3 = 1.0)

Inner pressure on layer 1 and on layer 2: T = +40°C ($f_{y,k,0.05,\,+23°C}$ = 21 MPa, A_3 = 1.2)

AMA – architectural membrane association e.V.
c/o Anhalt University of Applied Science
Seminarplatz 2a
06846 Dessau – Germany

Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

3.2. Design loads in SLS

3.2.1. Load Cases in SLS

LC SLS 01:	$g \oplus p_{nom} \oplus T$	T = + 40°C, permanent load, p = const., each load bearing layer
LC SLS 02:	$g \oplus p_{max} \oplus T$	T = + 23°C (lower layer), T = 3°C (upper layer), long term load, p = const., each load bearing layer
LC SLS 03-01:	$g \oplus p_{max} \oplus s_{uniform} \oplus T$	T = + 23°C, long term load,s ≤ p_{max}, p = const., lower load bearing layer(s), this LC is not decisive usually
LC SLS 03-02:	$g \oplus p_{max} \oplus s_{non\text{-}uniform} \oplus T$	T = + 23°C, long term load,s ≤ p_{max}, p = const., lower load bearing layer(s), this LC is not decisive usually
LC SLS 04-1:	$g \oplus p_{max} \oplus s_{uniform} \oplus T$	T = + 3°C, long term load, s > p_{max}, p not considered, considering load bearing layer(s) that are taking the load together)
LC SLS 04-2:	$g \oplus p_{max} \oplus s_{non\text{-}uniform} \oplus T$	T = + 3°C, long term load, s > p_{max}, p not considered, considering load bearing layer(s) that are taking the load together
LC SLS 05:	$g \oplus p_{max} \oplus w_{suction} \oplus T$	T = + 23°C* (outer layer), T = + 40°C (further load bearing layers), short term load, p x v = const., upper load bearing layer(s)
LC SLS 06:	$g \oplus p_{max} \oplus w_{pressure} \oplus T$	T = + 23°C, short term load, p x v = const., lower load bearing layer(s)
LC SLS 07-1:	$g \oplus p_{max} \oplus s_{uniform} \oplus w_{pressure} \oplus T$	T = + 23°C, short term load, s ≤ p_{max}, p x v = const., lower load bearing layer(s)
LC SLS 07-2:	$g \oplus p_{max} \oplus s_{non\text{-}uniform} \oplus w_{pressure} \oplus T$	T = + 23°C, short term load, s ≤ p_{max}, p x v = const., lower load bearing layer(s)
LC SLS 08:	$g \oplus$ water pond $\oplus T$	T = + 23°C, long term load,p = 0, considering load bearing layer(s) that are taking the load together

* If p_{nom}/p_{max} switch is controlled (e.g. by using snow- or temperature-sensors), the considered temperature (superimposed on p_{max}) can usually reduced to T = +3°C (instead of T = +23°C); inner layers in open buildings can be designed for wind loads superimposed with a temperature of t = +23°C, and in closed buildings with a temperature of t +40°C

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Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

4.0 Structural Analyses – Ultimate Limit State (ULS)

4.1. Design resistances in ULS

$f_{d,ULS} \leq f_{R,d,ULS}$ with the design value of the resistance in ULS: $f_{R,d,ULS}$

4.1.1. Reduction factors (A-factors) in ULS

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

with

$R_{k,0.05}$ = 5% fractile of the short term tensile strength at T = 23°C,

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

Table 6-3 A-factor description

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-axially 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-axially 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-axially determined strength values caused by temperature. change.
A_4	The reduction factor is meant to take into account the reduction of the strength of mono-axially 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-axially determined strength values caused by welding.

Table 6-4 A-factor values for ULS verification

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

* according to [Scm09]

** 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-dependency of A_3 is given by Figure 2.27 in [Mor07].

*** dependent on the tensile strength of the weld

AMA – architectural membrane association e.V.
c/o Anhalt University of Applied Science
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Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

Fig. 11 Applied reduction factors (A3-factors), ref. to [4], [5]

4.1.2. Reduction factor A3

The reduction factor A3 for consideration of the temperature influence on the characteristic stress limits in ULS is equal to that one, applied in SLS (see chapter 3.1.3).

4.1.3. Characteristic value of the Stress Limits in ULS

Table 6-5 5%-fractile values of mono-axial strengths of ETFE foil at T = 23°C [Mor07]

	5%-fractile values of mono-axial strength of ETFE-Foil at T = 23°C
mono-axial tensile strength of material	$f_{u,k,0.05,+23°C}$ = 47 N /mm²
mono-axial tensile strength of weld	$f_{u,k,SN,0.05,+23°C}$ = 30 N /mm²*

* example dependent on the tensile strength of the weld

Table 6-6 5%-fractile values of mono-axial strengths of ETFE foil at T = 3°C [Mor07]

	5%-fractile values of mono-axial strength of ETFE-Foil at T = 3°C
mono-axial tensile strength of material	$f_{u,k,0.05,+3°C}$ = 50 N /mm²
mono-axial tensile strength of weld	$f_{u,k,SN,0.05,+3°C}$ = 33 N /mm²*

* example dependent on the tensile strength of the weld

Fig. 12 Applied characteristic values of the Stress Limits in ULS, ref. to [4], [5]

4.1.4. Partial Safety factor (γ_m) in ULS

Table 6-7 γ_m for ULS verification

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

Fig. 13 Applied partial safety factor on the resistance (material) side in ULS, ref. to [4], [5]

AMA – architectural membrane association e.V.
c/o Anhalt University of Applied Science
Seminarplatz 2a
06846 Dessau – Germany
Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

4.1.5. Design values of stress limits in ULS

$$R_{d,SN,ULS,w_S} = \frac{f_{u,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1.1 \cdot 1.2 \cdot 1.0 \cdot 1.1 \cdot 1.0 \cdot 1.0 \cdot 1.57} = 20.62\ N/mm^2$$

$$R_{d,SN,ULS,S} = \frac{f_{u,k,F,0.05,+3°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{50}{1.1 \cdot 1.2 \cdot 1.3 \cdot 1.1 \cdot 1.0 \cdot 1.0 \cdot 1.57} = 16.87\ N/mm^2$$

$$R_{d,SN,ULS,p_{nom}} = \frac{f_{u,k,F,0.05,+23°C}}{\gamma_m \cdot A_0 \cdot A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_S} = \frac{47}{1.1 \cdot 1.2 \cdot 1.8 \cdot 1.1 \cdot 1.2 \cdot 1.0 \cdot 1.57} = 9.54\ N/mm^2$$

with

w_S wind suction,

S snow,

p_{nom} inner pressure.

The resistances R_d shall be compared and be larger than the design load F_d: $R_d > F_d$.

Fig. 14 Applied design values of resistances in ULS, ref. to [4], [5]

Note: The equations, shown in figure 14, are exemplary. The given uniaxial tensile strength values and assigned reduction factors are corresponding to the applied temperatures (basing on the following assumed maximal temperatures of the different ETFE-layers):

Wind suction, applied on layer 1 (upper layer): T = + 23°C ($f_{u,k,0.05,+23°C}$ = 47 MPa, A_3 = 1.0)

Snow load applied on layer 2 (lower layer): T = +3°C ($f_{u,k,0.05,+3°C}$ = 50 MPa, A_3 = 1.0)

Inner pressure on layer 1 and on layer 2: T = +40°C ($f_{u,k,0.05,+23°C}$ = 47 MPa, A_3 = 1.2)

4.2. Design loads in ULS

4.2.1. Load Cases in ULS

The consideration of the following load cases is recommended, if the respective load case may occur. If further load cases may occur, these have to be considered additionally. Load cases, that are not decisive justifiably, don't have to be analysed.

The temperature to be superimposed in the respective load case, depends on the maximum foil temperature, that may occur in the respective load case. The foil temperature relates to conduction, convection and radiation. However, the capability of the ETFE-foil to absorb thermal energy is low. The following foil temperatures are recommended to be applied for moderate climatic conditions (inside/outside the building). Especially hot climatic zones and desert zones, but also special applications and special environmental conditions may require the consideration of higher temperatures and, therefore, higher A3-factors.

LC ULS 01:	$1.35\ g \oplus 1.1\ p_{nom} \oplus T$	T = + 40°C, permanent load, p = const., each load bearing layer
LC ULS 02:	$1.35\ g \oplus 1.1\ p_{max} \oplus T$	T = + 23°C (lower layer), T = 3°C (upper layer), long term load, p = const., each load bearing layer
LC ULS 03-01:	$1.35\ g \oplus 1.1\ p_{max} \oplus 1.5\ s_{uniform} \oplus T$	T = + 23°C, long term load, $1.5\ s \leq 1.1\ p_{max}$, p = const., lower load bearing

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Phone: +49 340 5197 3745
Fax: +49 340 5197 3733
info@ama-forum.com
www.ama-forum.com

		layer(s), this LC is not decisive usually
LC ULS 03-02:	1.35 g ⊕ 1.1 p_{max} ⊕ 1.5 $s_{non\text{-}uniform}$ ⊕ T	T = + 23°C, long term load, 1.5 s ≤ 1.1 p_{max}, p = const., lower load bearing layer(s), this LC is not decisive usually
LC ULS 04-1:	1.35 g ⊕ 1.1 p_{max} ⊕ 1.5 $s_{uniform}$ ⊕ T	T = + 3°C, long term load, 1.5 s > 1.1 p_{max}, p not considered, considering load bearing layer(s) that are taking the load together
LC ULS 04-2:	1.35 g ⊕ 1.1 p_{max} ⊕ 1.5 $s_{non\text{-}uniform}$ ⊕ T	T = + 3°C, long term load, 1.5 s > 1.1 p_{max}, p not considered, considering load bearing layer(s) that are taking the load together
LC ULS 05:	1.35 g ⊕ 1.1 p_{max} ⊕ 1.5 $w_{suction}$ ⊕ T	T = + 23°C* (outer layer), T = + 40°C (further load bearing layers), short term load, p x v = const., upper load bearing layer(s)
LC ULS 06:	1.35 g ⊕ 1.1 p_{max} ⊕ 1.5 $w_{pressure}$ ⊕ T	T = + 23°C*, short term load, p x v = const., lower load bearing layer(s)
LC SLS 07-1:	1,35 g ⊕ 1.1 p_{max} ⊕ 1.5 ($s_{uniform}$ ⊕ 0.6 $w_{pressure}$) ⊕ T	T = + 23°C*, short term load, s ≤ p_{max}, p x v = const., lower load bearing layer(s)
LC SLS 07-2:	1,35 g ⊕ 1.1 p_{max} ⊕ 1.5 ($s_{non\text{-}uniform}$ ⊕ 0.6 $w_{pressure}$) ⊕ T	T = + 23°C*, short term load, s ≤ p_{max}, p x v = const., lower load bearing layer(s)
LC ULS 08:	1.35 g ⊕ 1.5 water pond ** ⊕ T	T = + 23°C*, long term load, p = 0, considering load bearing layer(s) that are taking the load together

* If p_{nom}/p_{max} switch is controlled (e.g. by using snow- or temperature-sensors), the considered temperature (superimposed on p_{max}) for layers that are in contact with snow can usually reduced to T = +3°C (instead of T = +23°C); inner layers in open buildings can be designed for wind loads superimposed with a temperature of t = +23°C, and in closed buildings with a temperature of t = +40°C

** If a water pond (or a snow pond or snow accumulation) is considered as an accidental load according to DIN 1990, the related partial safety factor can be reduced to 1.0. The breakdown of the air supply, is considered as such an accidential load usually, if the (in minimum two) fans in the blower unit and the electric power supply (with emergency electric power supply) are designed and operating redundantly.

5.0 Sources

[1] Moritz, K., Drawings, Germany, 09/2017

[2] Moritz, K., ETFE-foil as Load Bearing Element, Dissertation, TU Munich 2007

[3] Schiemann, L., Load Bearing Behavior of ETFE-Foils in Biaxial Stress States, Dissertation, TU Munich 2009

[4] Stranghöhner, N., Uhlemann, J. et al. "Prospect for European Guidance for the structural design of Tensile Membrane Structures", 2016

[5] Houtmann, R. et al, Annex A5 of the TensiNet European Design Guide for Tensile Structures, 2013

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