AMA

Design Recommendations

Designing Air inflated Structures

Air Supply Systems for ETFE-Foil Cushions

state: 2017-10-25

copyright: Karsten Moritz

contact: k.moritz@taiyo-europe.com

published: www.amaforum.com

AMA design recommendations have been created for the orientation and support of interested readers. The shown information is developed and compiled to the author's best knowledge and belief. Despite careful processing and correction, liability for the content cannot be accepted neither by the author nor by the Architectural Membrane Association e.V. (AMA). Please contact the author for mistakes you may have found.

Table of content

1.0 Purpose

These design recommendations refer to aspects of the constructional design of pneumatic structures, especially air inflated (pneumatically supported) cushions. Currently, this construction method is made of ETFE-foils preferably. The document focus on the principles of the load bearing behavior of ETFE-foil cushions and on the air supply system, which is necessary for the inflation with air, for flushing of the enclosed chambers and for stabilization of the different layers.

Meanwhile, certain construction methods have proven to be favorable or unfavorable. The document shows the various design principles and options with short explanations of the advantages and disadvantages.

2.0 Typology

Pneumatic structures are classified by the following principal types (Fig. 1).
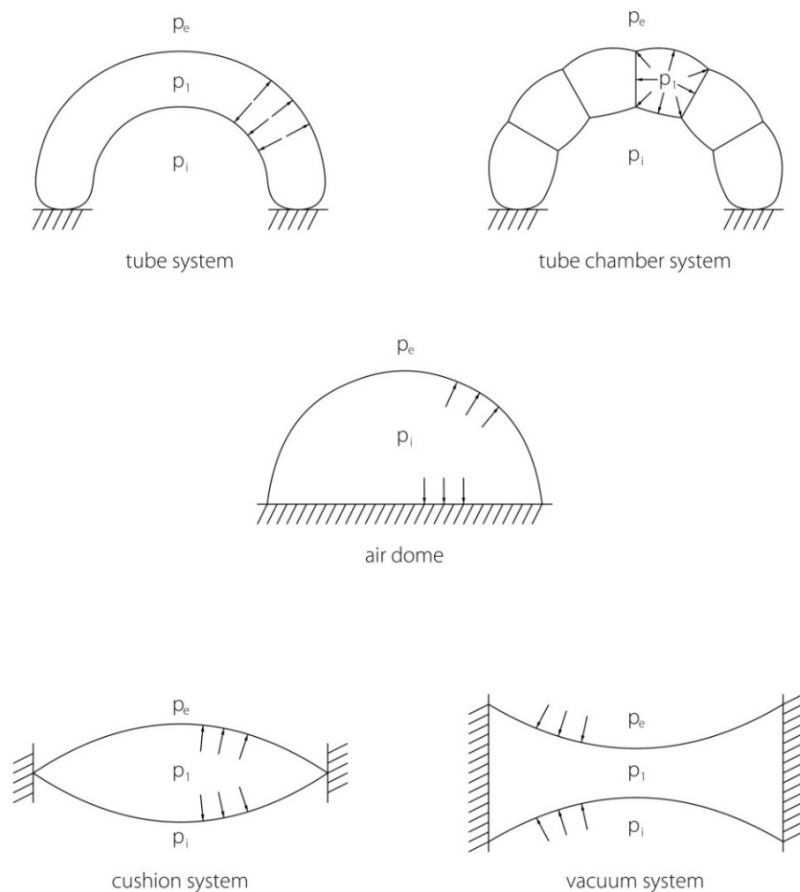
Fig. 1   Typology of pneumatic structures [1] initially based on [5]

Usually air domes, cushion systems and vacuum systems are characterized by a quite low pressure difference up to approximately 600 Pa, sometimes a bit more, to the environmental atmospheric pressures p_e (e = external) and p_i (i = internal). Conversely, tube systems usually have a much bigger pressure difference of more than 1 bar (100,000 Pa) to the atmospheric pressure, to ensure appropriate deflections, also in cases of external design loads induced by wind and snow.
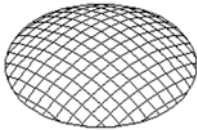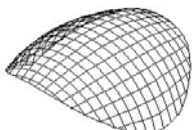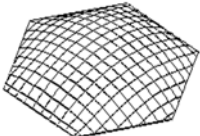
3.0 Air inflated cushions
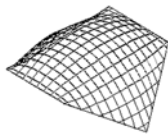
3.1. Principle shapes
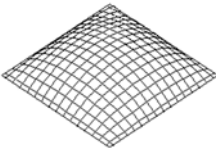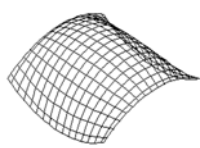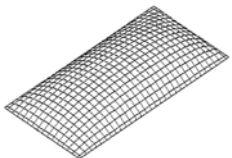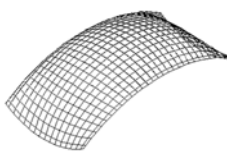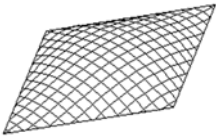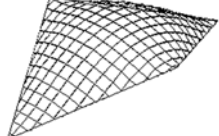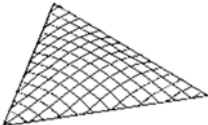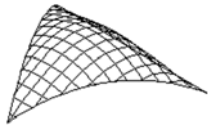
Shape	planar boundary	spacial boundary
circular		
polygonal		
square		
rectangular		
rhombic		
trianglular		

Fig. 2   Pneumatic structures – air inflated cushions – principle shapes / surfaces [2]

3.2. Load bearing behavior

Using the boiler formula the principal forces in a layer of a square shaped cushion (Fig. 3) in a biaxial stress state (inner pressure) can be evaluated roughly as follows.

uniaxial load transfer:
$$F = r \cdot q$$

biaxial load transfer:
$$p = \frac{F_1}{r_1} + \frac{F_2}{r_2}$$

The equations don't consider either transversal contraction of the material nor the deformation of the initial geometry.

© L. Schiemann
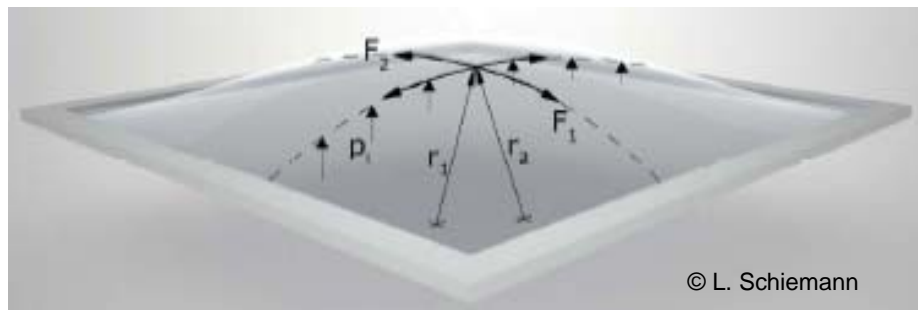
Fig. 3   Principal forces in the outer layer of a square cushion exposed by inner pressure [3]

actio: |Σ FH| = FH1 + FH2 + FH3   = reactio |FH|
actio: |Σ FV| = FV1 + FV2 - FV3   = reactio |FV| = 0   © K. Moritz
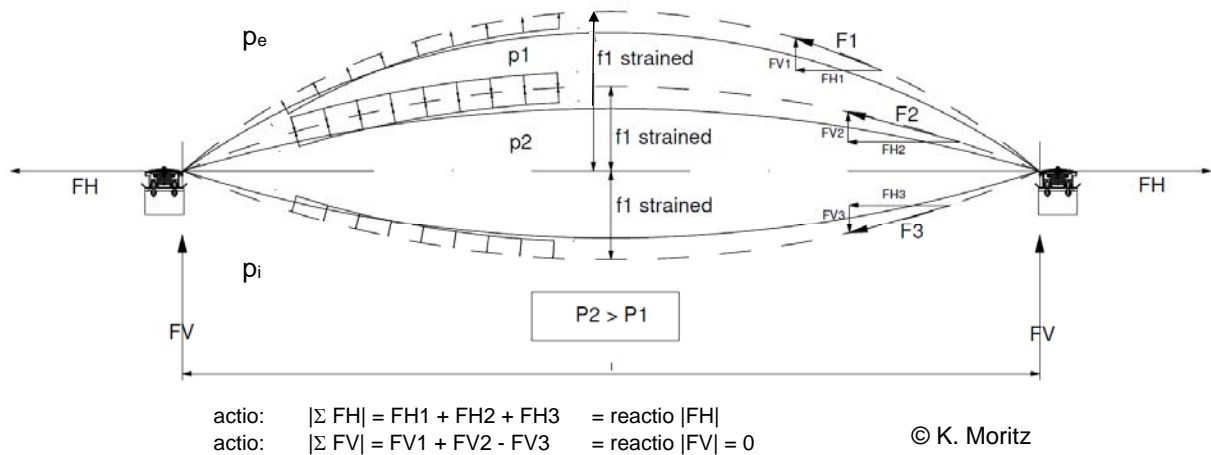
Fig. 4   Principle of the uniaxial load bearing behavior of a pneumatic cushion (3-layer system) - load case pre-stress (internal pressures p_1 and p_2) [1]

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

© K. Moritz

Fig. 5   Principle of the uniaxial load bearing behavior of a pneumatic cushion (3-layer system) - load case wind suction Ws [1]

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

© K. Moritz

Fig. 6   Principle of the uniaxial load bearing behavior of a pneumatic cushion (3-layer system) - load case uniform snow S [1]

p_e

S

ΣF_H

f1 strained, f2 strained, f3 strained

ΣF_V

FH

FV

p_i

FH

FV

L

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

© K. Moritz

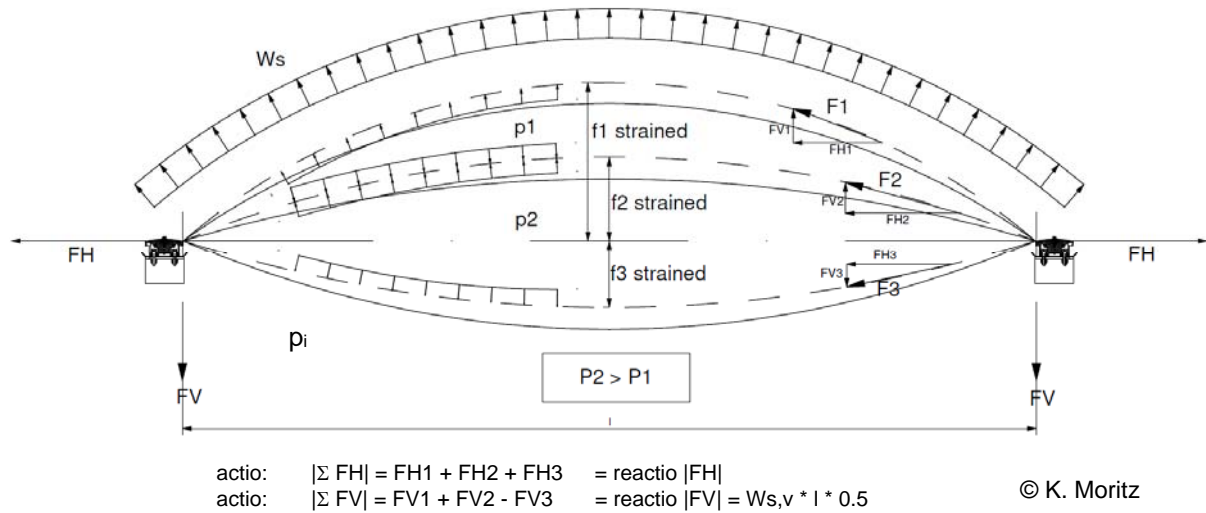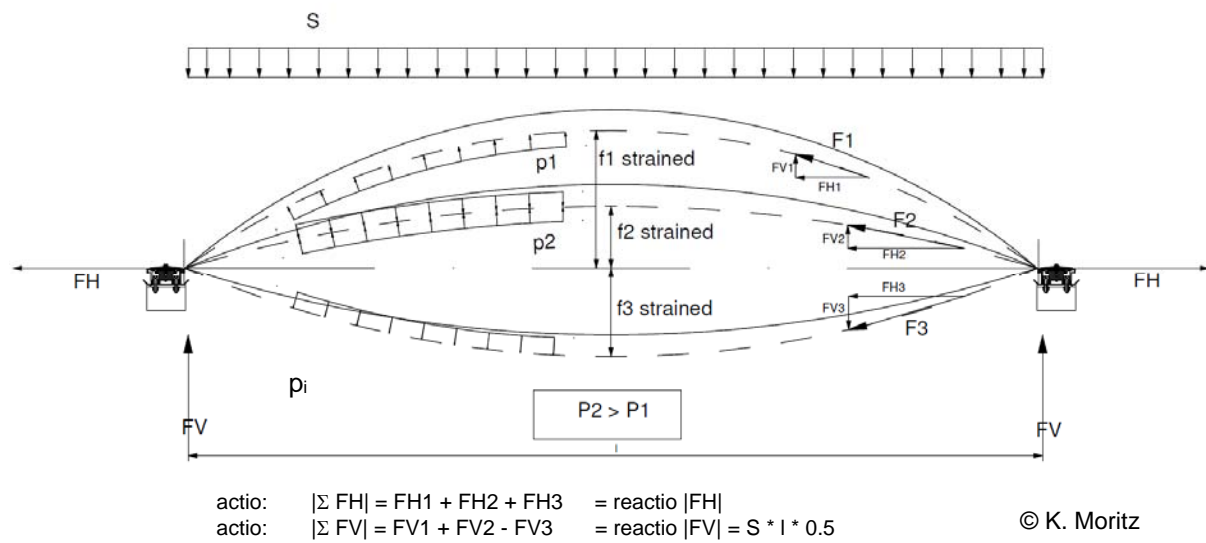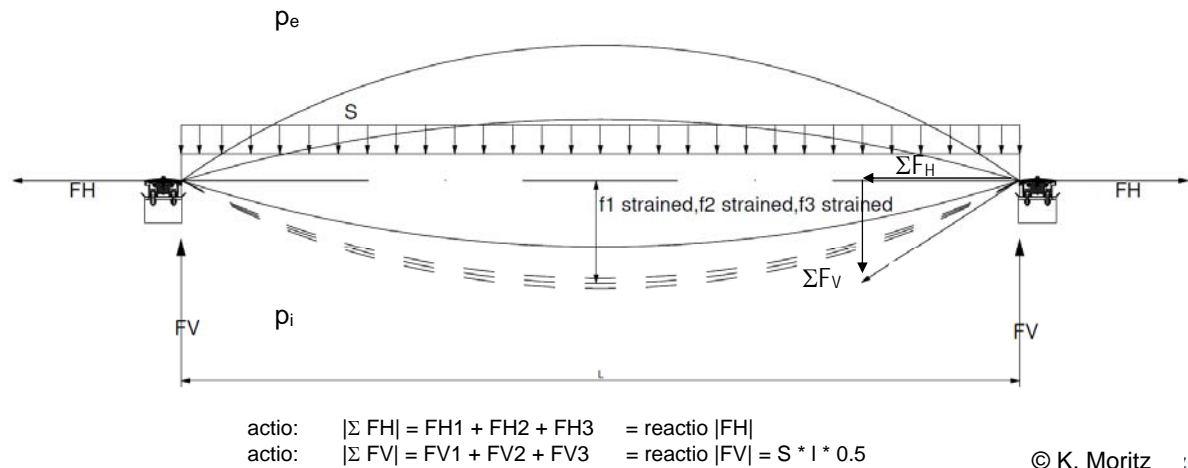Fig. 7   Principle of the uniaxial load bearing behavior of a pneumatic cushion (3-layer system) - load case uniform snow S on a deflated cushion or if the snow load S exceeds the internal pressure in the cushion [1]

3.3.   Assembly situations

Air inflated cushions can be used, for example, as roof, façade or as complete building envelope. The distinction of the three ranges of inclination (horizontal, inclined and vertical) has been chosen, because of the following important reasons (Fig. 8):

- The applicability of the Eurocode EN 13830: 2015 - Curtain walling - Product standard refers to "vertical" façades (curtain walls) with an inclination of 75° and more [4].

- Especially cushions with an inclination lower than 15° ("horizontal" cushions) are endangered due to the risk of water ponds. For usual cushion geometries with inclinations of 15° and more, the water normally can drain above the eave. Nevertheless, the investigation of the water pond risk should be done also for such structures.
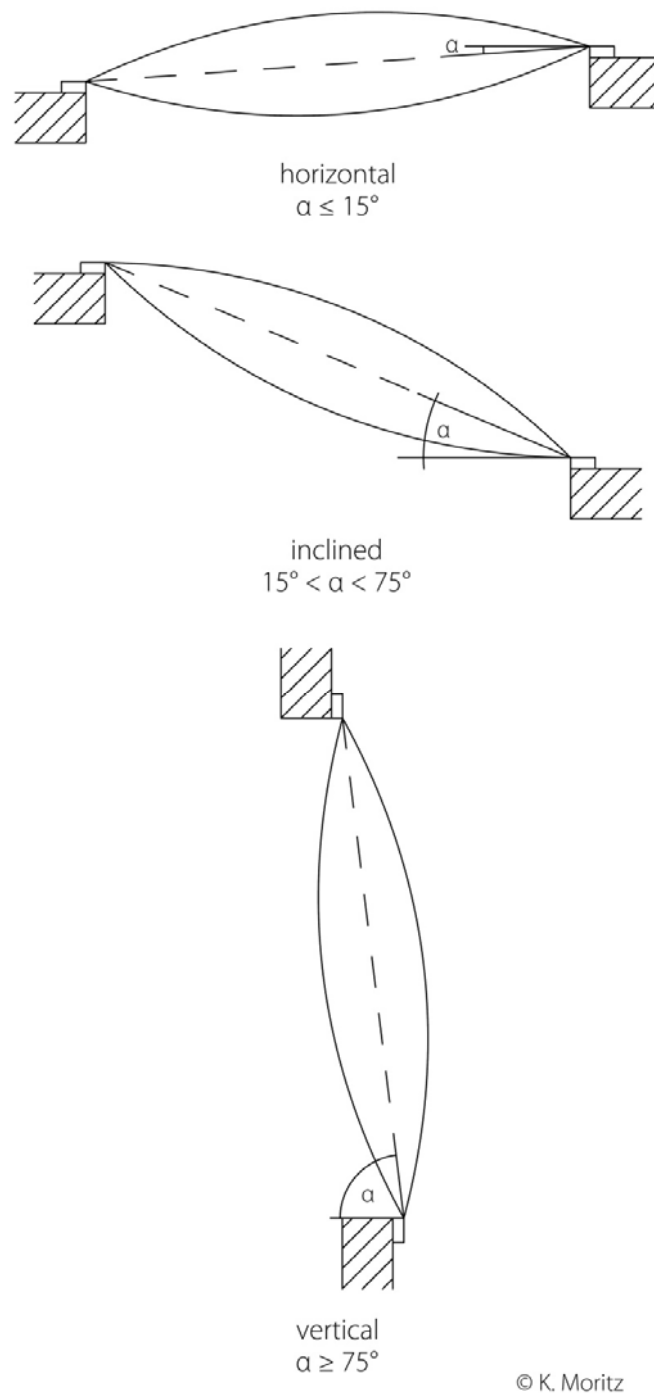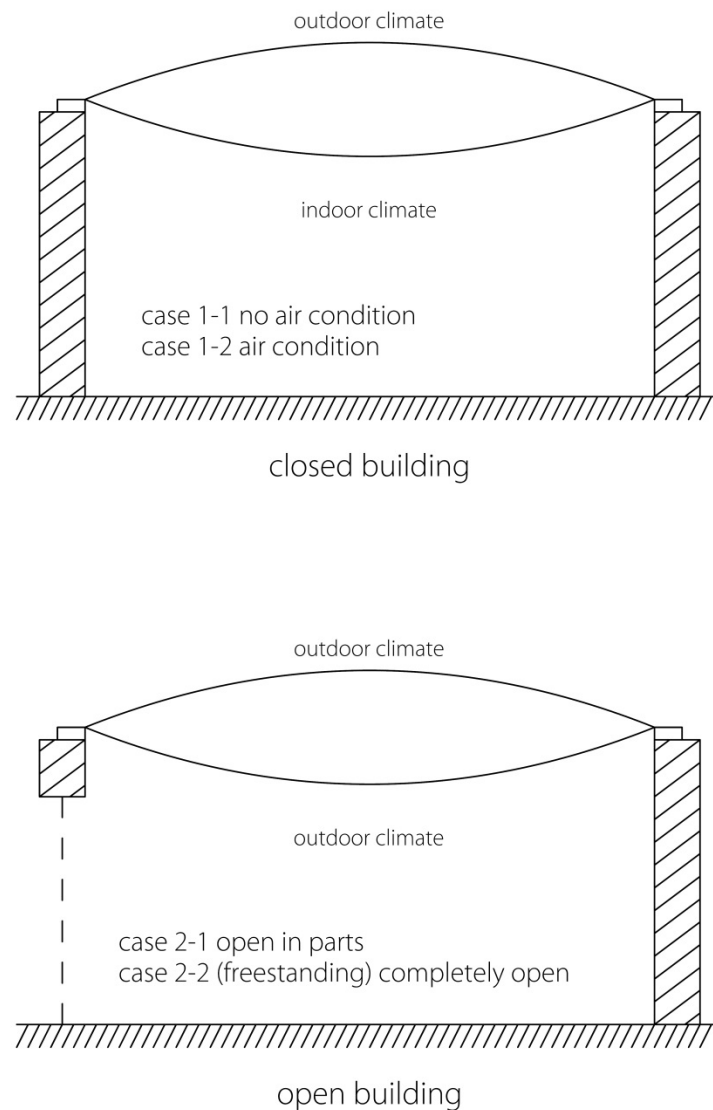
horizontal
α ≤ 15°

inclined
15° < α < 75°

vertical
α ≥ 75°

© K. Moritz

Fig. 8   Pneumatic structures – cushion systems - assembly situation - inclination [1]

outdoor climate

indoor climate

case 1-1 no air condition
case 1-2 air condition

closed building

outdoor climate

outdoor climate

case 2-1 open in parts
case 2-2 (freestanding) completely open

open building

© K. Moritz

Fig. 9   Pneumatic structures – cushion systems - assembly situation - openness of buildings [1]

Membranes, also ETFE-foils, are sensitive to changes in temperature. The temperature can influence the material stiffness, the deformations and the design limits of plastic materials significantly (tensile strength, yield stress etc.). Each layer can achieve a different temperature in the same load case. For example, the temperature of the inner (lower) layer has a different temperature and material resistance (to wind pressure) as the outer (upper) layer (to wind suction). Therefore, the question, if the building is open or closed is of importance for the temperature approach for the specific layer and finally for the reliability of the structural analyses, which are done layer by layer.
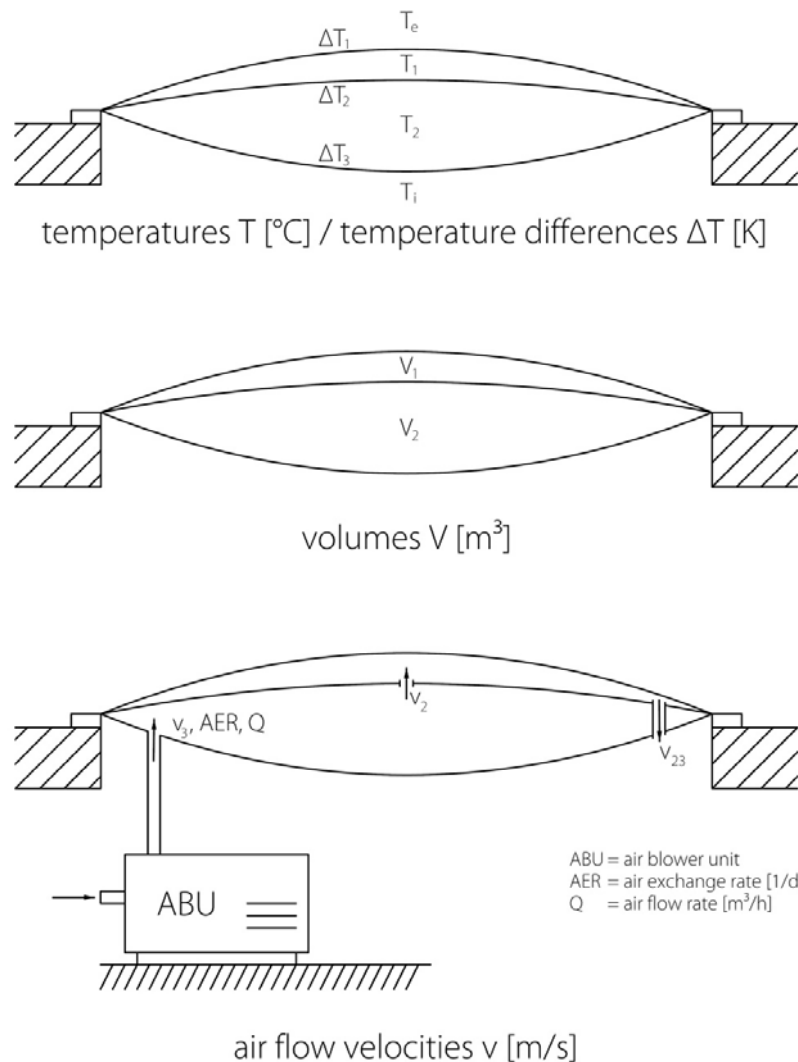
3.4. Parameters (nomenclature)
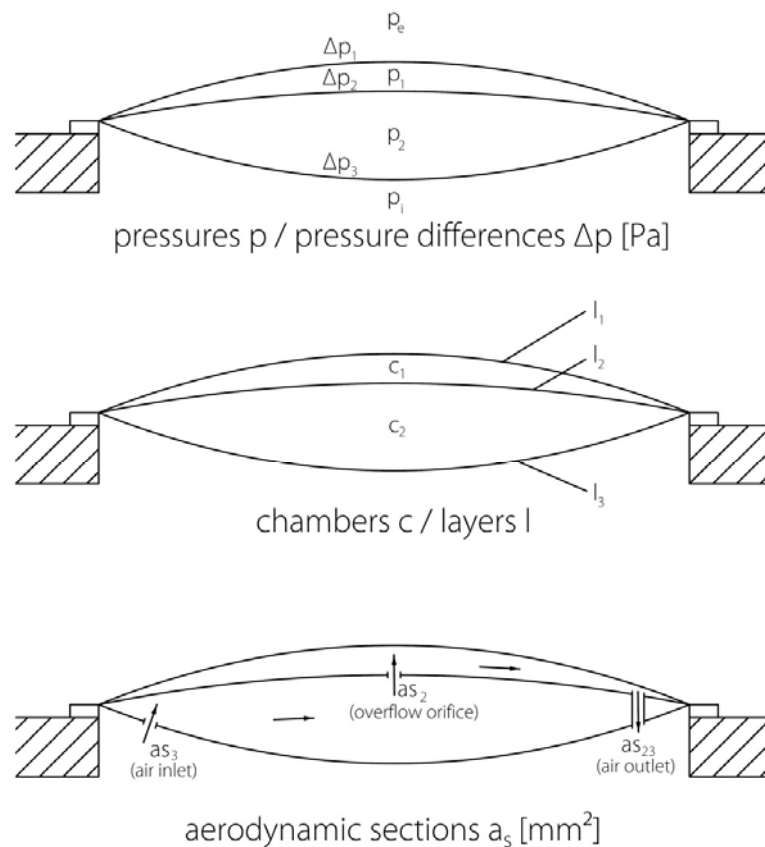
Fig. 10   Pneumatic structures – cushion systems – parameters (nomenclature): pressures p / pressure differences Δp, chambers c, layers l, aerodynamic sections a_s [1]

The unification of parameters, units and indicees according to the Eurocode and to the sysetem of SI-units is imporatant, to avoid missunderstandings. Air supported cushions can be described by the following parameters and acronyms:

- pressure p, pressure difference Δp [Pa]
- chambers c, layers l [-]
- aerodynamic sections (valves) [mm²]
- temperatures T [°C], temperature difference ΔT [K]
- volumes V [m³]
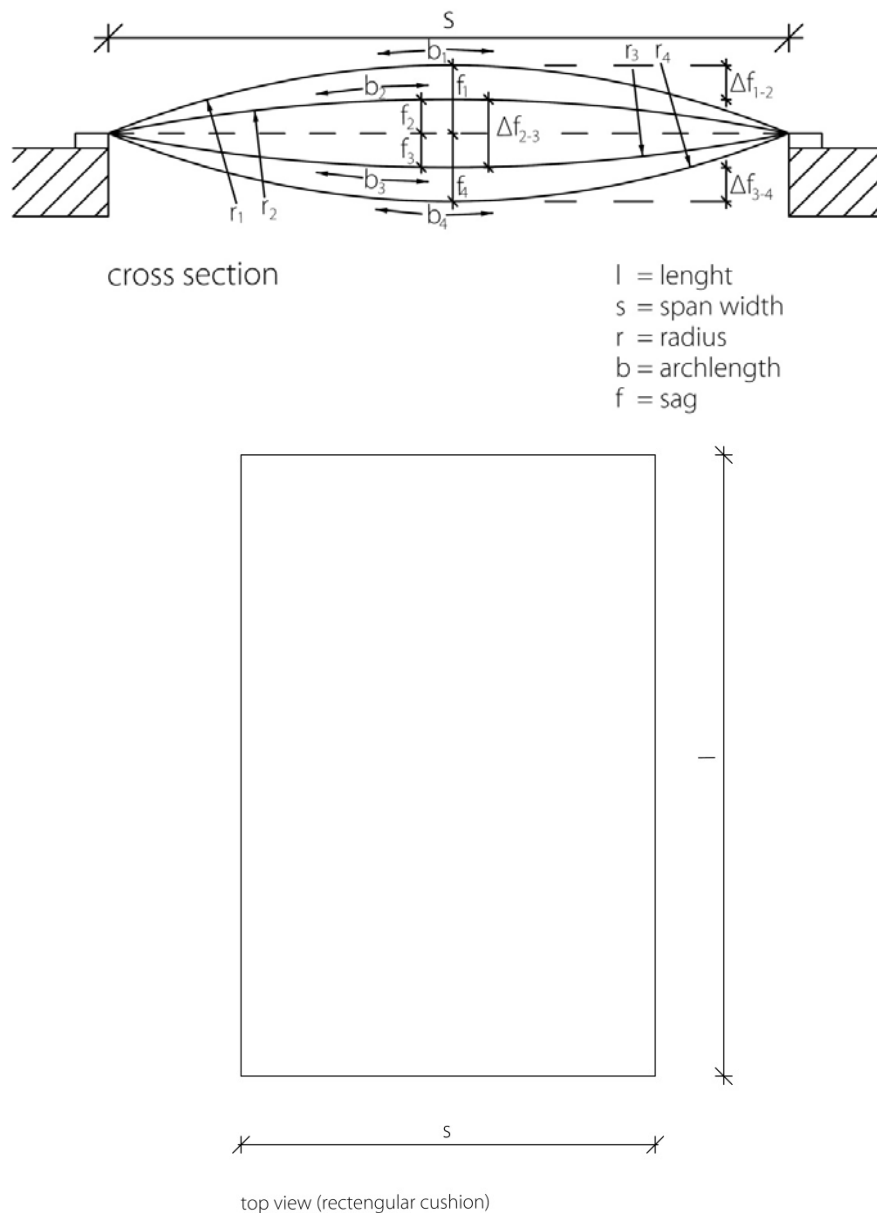- airflow velocities v [m/s]
- air exchange rate AER [1/d]
- airflow rate [m³/h]

Fig. 11 Pneumatic structures – cushion systems – parameters (nomenclature): temperatures T / temperature differences ∆ T, volumes V and airflow velocities v [1]

Air inflated cushions need an air supply for their stabilization, for wrinkle-free surfaces, for the curvature of the different layers (pressure differences) and sometimes for a pneumatic shading system, by using one or more moveable middle layers. Usually, the air supply is provided by an air blower unit (ABU) and an air duct system. The blower unit delivers an overpressure related to the atmospheric pressure around, which leads to overpressures of approximately 600 Pa, sometimes a bit more, inside the cushions.

3.5. Dimensions

The following dimensions decribe the geometrie of air inflated cushions entirely:
length l [m], span width s [m], radius r [m], arc length b [m] and sag f [m] (Figure 11).

cross section

l = lenght
s = span width
r = radius
b = archlength
f = sag

top view (rectengular cushion)

© K. Moritz

Fig. 12   Pneumatic structures – cushion systems –dimensions [1]

3.6. Number of layers

The thermal insulation of an air supported ETFE-foil cushion system improves with the number of layers. Rough reference values can be given, based on calculations done according to the respective Eurocodes. However, the UW-value depends on some parameters, like the thermal insulation of the clamping profile and the ratio of profiles (opaque part) and cushions (transparent part).
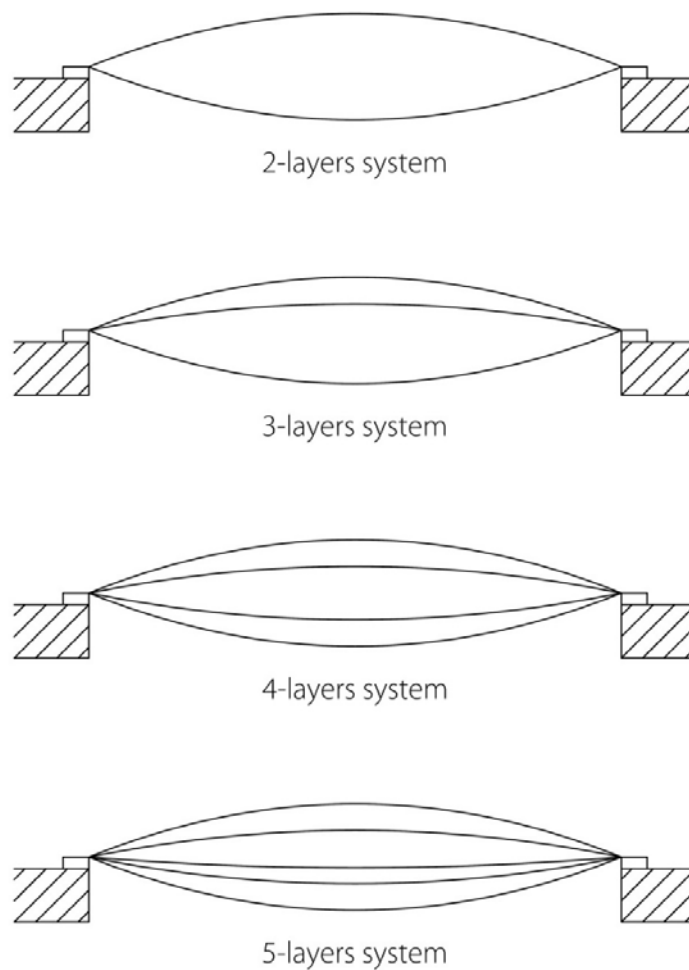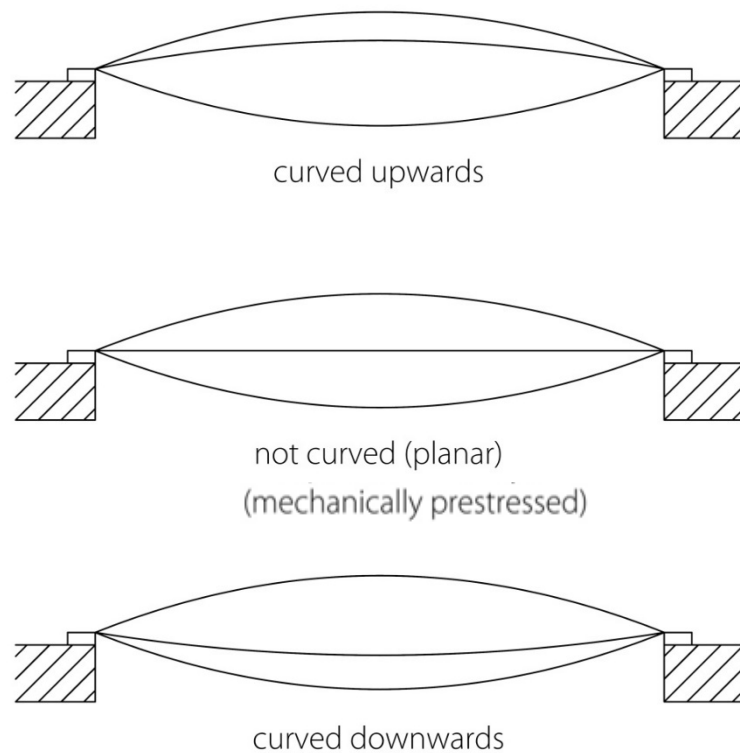

© K. Moritz

Fig. 13   Pneumatic structures – cushion systems – number of layers (2-5 layers systems) [1]

U-values as Reference values	U_g [W/(m²K)]	U_f [W/(m²K)]	U_w* [W/(m²K)]	Indices
				g = glass (transparent part / ETFE)
2 layers	2.6		3.0	f = frame (opaque part / extrusion profile)
3 layers	1.7	8.7	2.0	w = window (transparent part plus opaque part)
4 layers	1.5		1.7	
5 layers	1.3		1.5	

Table 1: Reference U-values for 2-5 layers cushions [1]

3.7. Curvature of middle layers

curved upwards

not curved (planar)
(mechanically prestressed)

curved downwards

© K. Moritz

Fig. 14   Pneumatic structures – cushion systems - curvature of middle layers [1]

In the first years of building with ETFE-foil cushions, the middle layer (layer 2 of a 3-layers cushion) was realized as a flat surface, mechanically pre-tensioned. The disadvantages of these systems are the following:

- some load cases, like snow, that exceeds the inner over pressure in the cushions, can deform the planar layer plastically

- layers, which are not curved, don't participate significantly to the load bearing, only if they are deformed strongly

Today, the middle layers are built curved and pre-stressed by using pneumatic overpressure. Sometimes the middle layer is curved upwards, sometimes downwards. A middle layer, which is curved upwards, can be applied structurally for load cases of wind suction as well as snow loads, which are exceeding the overpressure inside the cushion.

3.8. Separation of layers

The separation of layers circumferentially to the cushions boundary can improve the thermal insulation of the system and the sound/noise insulation too.
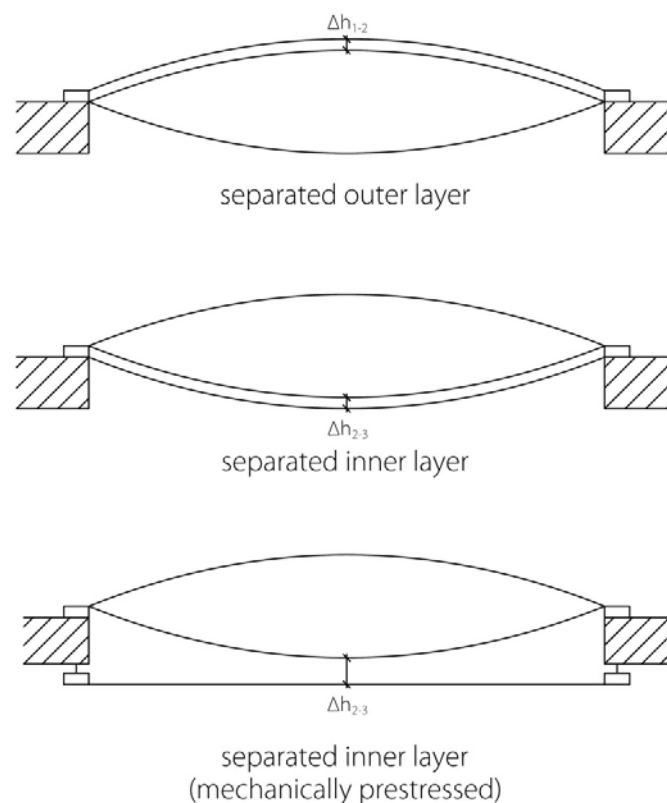

Fig. 15   Pneumatic structures – cushion systems - separation of layers [1]

4.0   Air supply systems

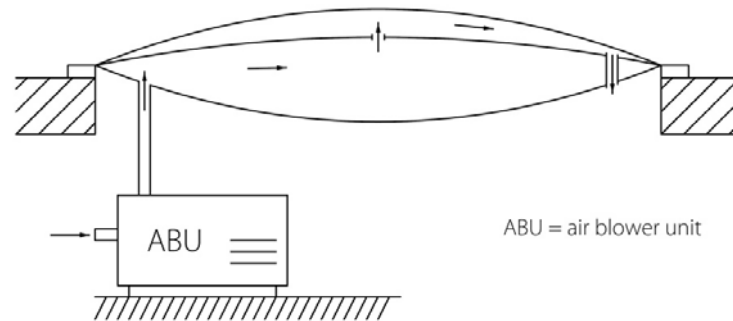Today, different air supply systems are available. We differentiate between the following principle methods:

- Stationary Air System (SAS) - system, without air outlet, which is just pumped up
- Open Air Systems (OAS) - system with air outlet to the environment (indoor)
- Double Open Air Systems (D-OAS) - system with air outlet and with two blower units (ABU'S) for the supply of two different pressures
- Double Open Air Systems with pressure reducers (D-OAS-PR) - system with air outlet and with one blower unit (ABU), but with pressure reducer for creating a second lower pressure
- Circuit Air Systems (CAS) - closed air supply system, built as a loop (circuit)
- Double Circuit Air Systems (D-CAS) - two closed air supply systems, built as loops (2 circuits) with different pressures

4.1.   Stationary systems, open systems and circuit systems
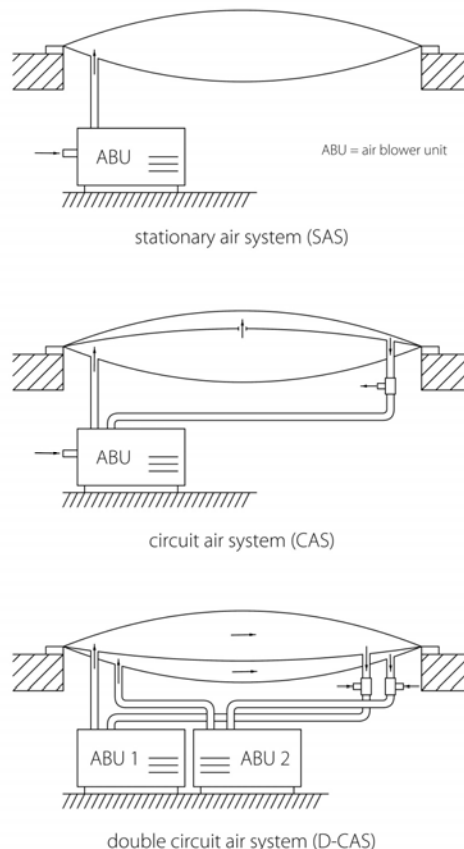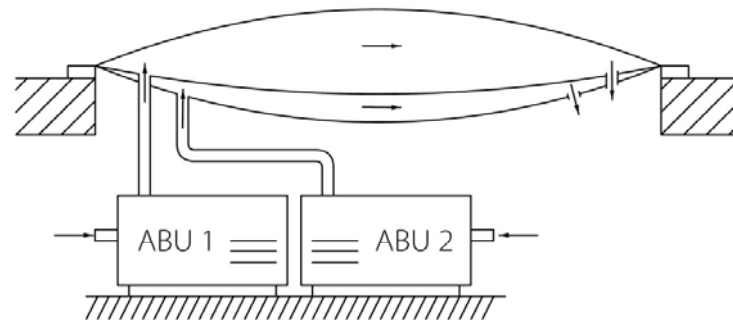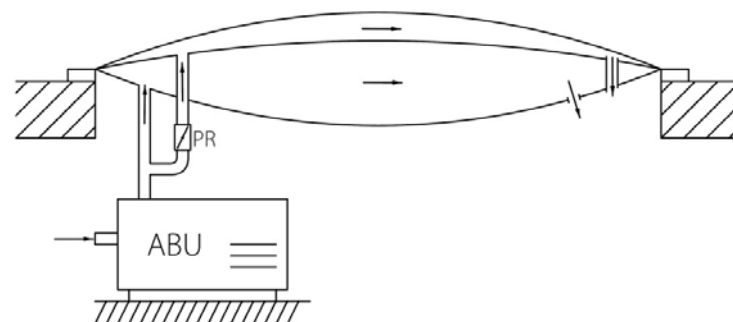

© K. Moritz

Fig. 16   Pneumatic structures – air supply systems – stationary air system (SAS), circuit air system (CAS) and double circuit air system (D-CAS) [1]

open air system (OAS)

ABU = air blower unit

double open air system (D-OAS)

double open air system with pressure reducer (D-OAS-PR)

© K. Moritz

Fig. 17   Pneumatic structures – air supply systems – open air system (OAS), double open air system (D-OAS) and double open air system with pressure reducer (butterfly valve) [1]
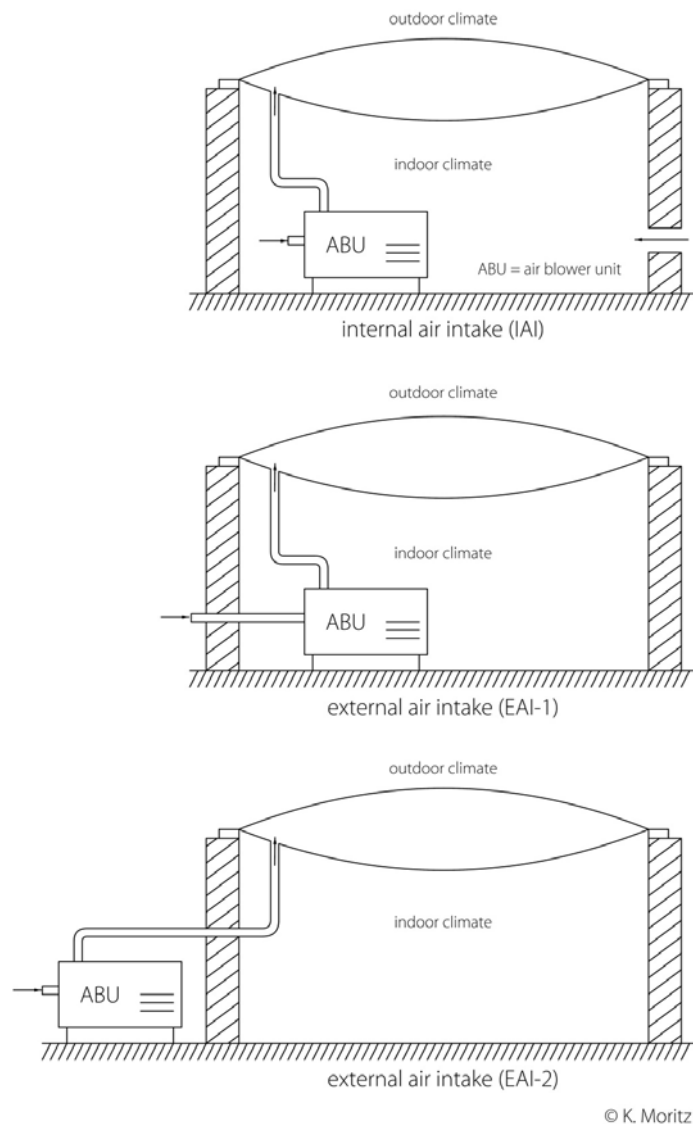
4.2. Air intake

Fig. 18   Pneumatic structures – air supply systems – air intake [1]

For the conditions of the inflating air it is very important, where the air blower unit takes the air from - inside (internal) or outside (external). The expected inside and outside climates (air temperature and air humidity) can be found in the relevant codes, like EN 4108 in Europe. From this point of view, the external air intake is to prefer usually, because the water amount [g/m³] of cold air is lower than of warm air with the same relative humidity [rel H in %].

4.3. Airflow Principles (Air Management)

The sufficient air management guarantees a permanent airflow inside the air supported cushions. The airflow is necessary for the avoidance or minimization of condensation inside the cushion and to create a pressure difference at the middle layer. A curved middle layer (for example layer 2 in a 3-layers cushion) cannot be realized without a pressure difference.
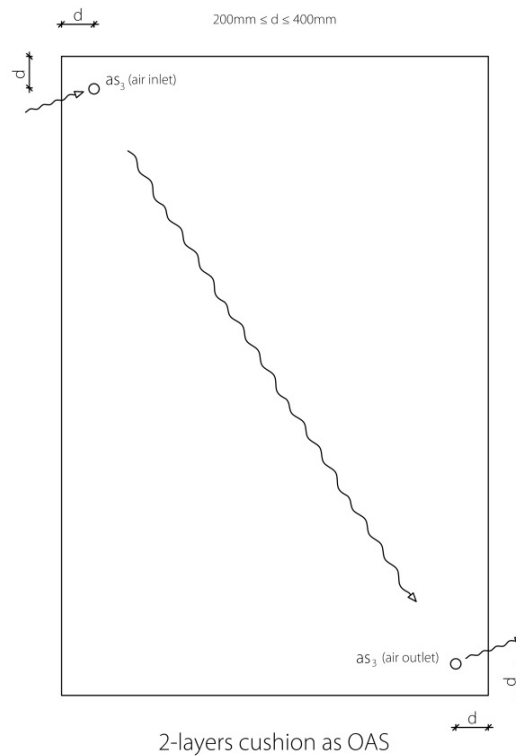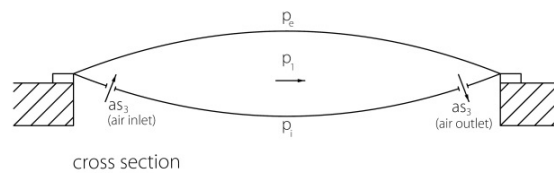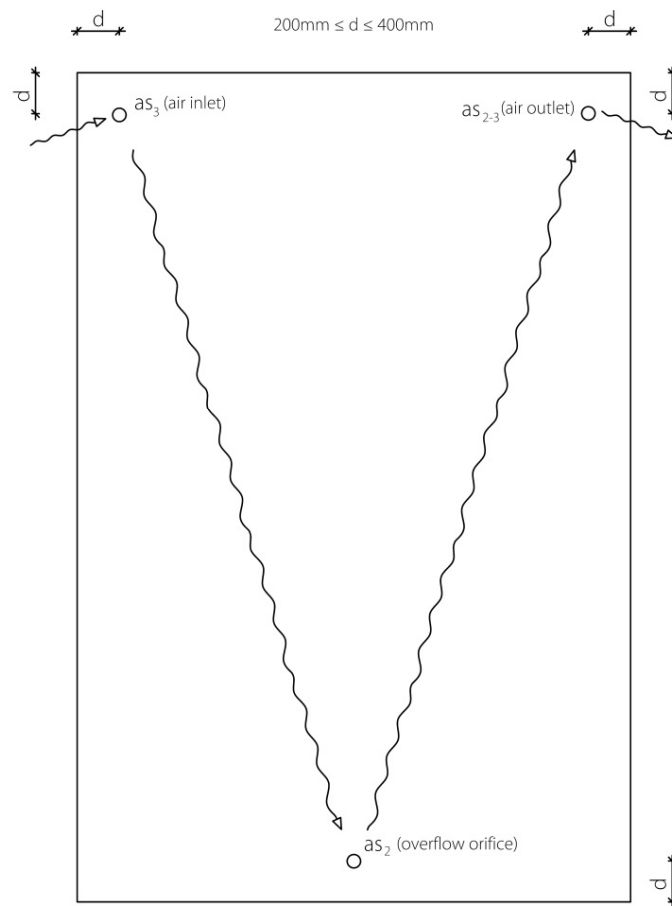

© K. Moritz

Fig. 19   Pneumatic structures – air supply systems – airflow - rectangular 2-layers cushion as open air system (OAS) [1]

cross section

200mm ≤ d ≤ 400mm

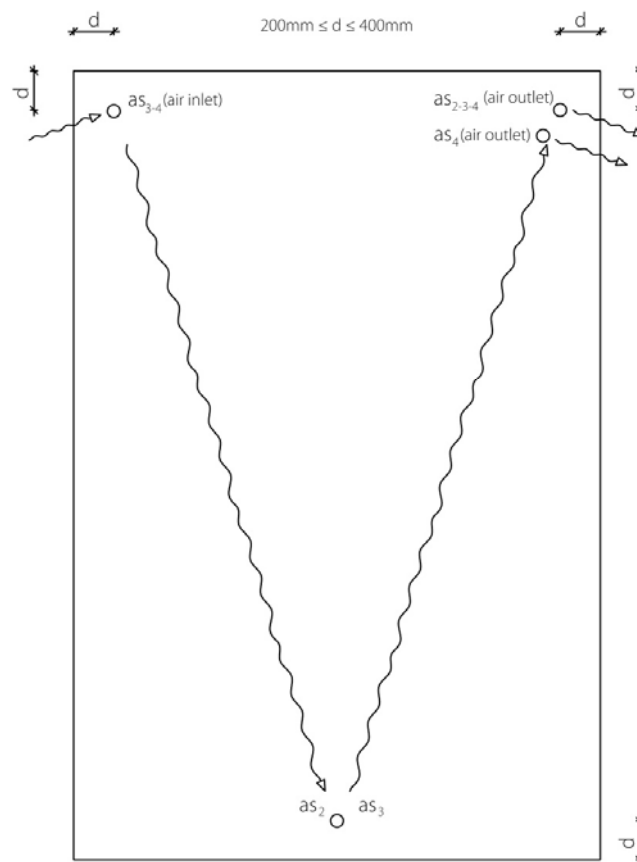as_3 (air inlet)

as_{2-3} (air outlet)

as_2 (overflow orifice)
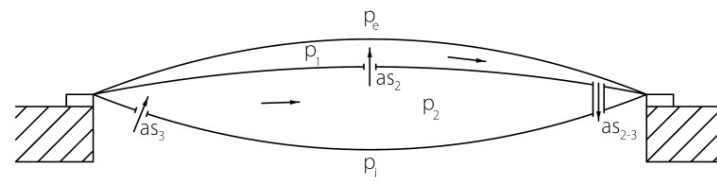
3-layers cushion as OAS

© K. Moritz

Fig. 20   Pneumatic structures – air supply systems – air management rectangular 3-layers cushion as open air system (OAS) [1]

cross section

200mm ≤ d ≤ 400mm

as_{3-4} (air inlet)

as_{2-3-4} (air outlet)

as_4 (air outlet)

as_2 as_3
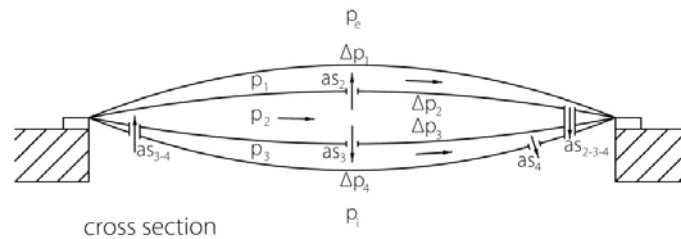
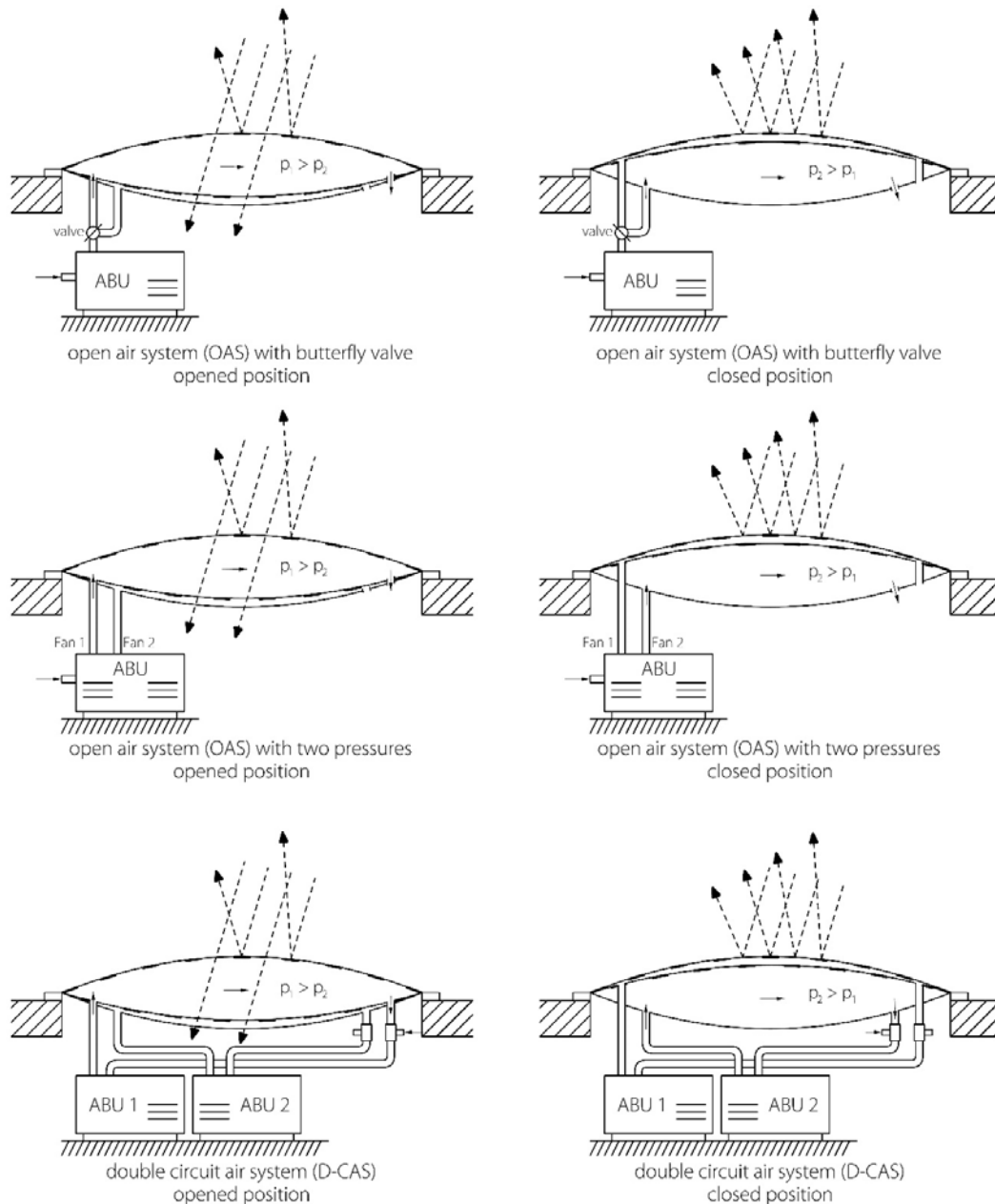4-layers cushion as OAS

© K. Moritz

Fig. 21   Pneumatic cushions – air supply systems – air management 4-layers cushion as open air system (OAS) [1]

5.0   Pneumatic Shading Systems

open air system (OAS) with butterfly valve
opened position

open air system (OAS) with butterfly valve
closed position

open air system (OAS) with two pressures
opened position

open air system (OAS) with two pressures
closed position

double circuit air system (D-CAS)
opened position

double circuit air system (D-CAS)
closed position

© K. Moritz

Fig. 22   Pneumatic cushions – air supply systems –types of pneumatic shading systems [1]

6.0   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]   DIN EN 13830: 2015-07 Curtain walling - Product standard; German version EN 13830: 2015

[5]   Herzog, Thomas (author), Minke, Gernot, Eggers, Hans, Pneumatische Konstruktionen - Bauten aus Membranen und Luft, Hatje Cantz Verlag, ISBN-10: 3775700838, ISBN-13: 978-3775700832, 1986