TensiNet sessions at Advanced Building Skins 2021, Bern

Two TensiNet sessions on Membrane Architecture were held chaired by Carol Monticelli and Carl Maywald. The abstract or paper of Fevzi Dansik, Gerd Schmid, Claudia Lueling, Bernd Stimpfle and Jürgen Holl is included in this document.

Skins from Fabrics and Foils - *Chair: Carol Monticelli*

In the session Skins from fabrics and foils ***Carol Monticelli*** presents the tendencies, challenges, sustainability and life cycle of tensile structures in Europe. Interesting case studies are presented by ***Fevzi Dansik*** on the Batumi Stadium and by ***Gerd Schmid***, who will focus on the new design language for urban architecture. ***Allan Hurdle*** finds an answer on the question "why limited combustible membranes are important". ***Claudia Lüling*** finishes the session by showing results from research about textile based, lightweight construction at Frankfurt University of Applied Sciences.

- **Contemporary tensile structures in Europe: Tendencies, challenges, sustainability and life cycle**

  Marijke Mollaert, Vrije Universiteit Brussel, Belgium; Carol Monticelli, Politecnico di Milano, Italy; Alessandra Zanelli, Politecnico di Milano, Italy

- **Batumi Stadium: from design to installation**

  Fevzi Dansik, Asma Germe Membran Sistemleri Mim., Istanbul, Turkey

- **New design language for urban architecture: Bus stations, tram stations, transfer hubs**

  Gerd Schmid, formTL, Germany

- **Why limited combustible membranes are important**

  Allan Hurdle, AKH Services Ltd, Colchester, United Kingdom

- **Lightweight design with spacer fabrics**

  Claudia Lueling, University of Applied Sciences, Frankfurt, Germany

Building Membrane Cladding Systems - *Chair: Carl Maywald, Vector Foiltec GmbH, Bremen, Germany*

The session Building Membrane Cladding Systems starts with a presentation by ***Ben Runhaar*** on Low haze ETFE film for façade solutions. ***Bernd Stimpfle*** questioning if technical specifications are needed for building with foils and fabrics. ***Carl Maywald*** shows ETFE applications along with an outlook on the durability of foils commonly used in tensile architecture. One of today's major functions of tensile building envelopes is highlighted in the presentation of ***Monika Rychtáriková*** from Leuven University. She talks about research in the acoustical effects of fabric façades. The insight in engineering ETFE façades is deepened by a presentation of ***Felix Surholt***. ***Maxime Durka*** shows the possibilities of frame-supported membrane structures and ***Jürgen Holl*** gives an insight in calculating and form finding of tensile structures.

- **Low haze ETFE film for façade solutions**

  Ben Runhaar, AGC Chemicals Europe, Amsterdam, Netherlands

- **Do we need technical specifications for membrane structures?**

Bernd Stimpfle, TensiNet, Germany

- **ETFE applications, durability of foils commonly used in tensile architecture**

  Carl Maywald, Vector Foiltec, Bremen, Germany

- **Acoustic benefits of structural skins used as roof or façade construction**

  Monika Rychtarikova, KU Leuven, Brussels, Belgium

- **Recent development in European ETFE design**

  Felix Surholt, Universität Duisburg-Essen, Germany

- **Frame-supported membrane structures**

  Maxime Durka, Sioen, Belgium

- **Analytical calculation of membranes and foils for building skins**

  Jürgen Holl, technet, Stuttgart, Germany

Tensioned Roof and Façade of Batumi Stadium: from Design to Installation

Dr. Fevzi DANSIK, Dr. Meltem SAHIN

Mimar Sinan Fine Arts University and Managing Partners of AG

Key words: Fabric Roof, Tensioned Fabric Stadium

ABSTRACT

The Batumi Football Stadium has rather different roof design with its folded plate like form made of tensioned fabric than that of the usual fabric roofs. Furthermore, the design of the façade with its overlapping leaves made of tensioned fabric has unique visual affect. Apart from its esthetical aspects, the design conditions of the roof are extremely challenging because of the snow loading. It is the aim of this paper to present all the challenges involving to build these unique roof and façade systems made of tensioned fabric starting from the design to the final installation.

The stadium has been designed according to UEFA 4 category rules. The capacity of it is 20.000 seats. The roof area is approximately 20.000 m^2 and the façade area is 14.000 m^2. This stadium has a very significant importance with the nation of Georgia since it has been the first stadium built after nearly 60 years. Hence, the construction progress was followed very closely. This was elongating the decision progress, but the deadlines were not to be affected.

The main challenge with the roof design was to carry the snow load which is 3 kN/m^2. This has been only possible to allow the fabric to touch the steel elements under extreme snow loading and hence transferring some part of the load to the steel elements. An iterative algorithm has been developed to define the amount of the loading to be applied to these elements. This procedure is also presented in the paper briefly.

The main challenge with façade is to model the geometry of it. Moreover, the design of the tensioning system which is not visual from the front side was also big task. Furthermore, the façade installation process was another big task since it was difficult or almost impossible to reach the overlapping modules from the behind of the façade.

Batumi located by Black Sea and hence get a lot of rain and wind during the winter and spring times. Unfortunately, the installation of the roof cover has planned during the winter of 2019 by the main contractor. Hence, it has been extremely difficult to install roof cover.

The aim of this paper to present the all the steps that involves to make one nation’s dream to become a reality.

New design language for urban infrastructure: Bus stations, tram stations, transfer hubs

Gerd Schmid
formTL ingenieure für tragwerk und leichtbau GmbH
gerd.schmid@form-tl.de

Abstract

The paper is about a new design language for urban infrastructure: Bus stations, tram stations, transfer hubs with a view to long-term visual value, low maintenance requirements and recognisability. This modern design language is now associated with formTL.

Keywords: Mobile society, encased structure, ETFE foil, circulating air system, functional urban art

1. Infrastructure in the context of Switzerland's demography

The Swiss population is very mobile: every year they travel 11,000 km by road and rail and another 9,000 km by plane. 1/3 use public transport to get to work.

Switzerland had an average population density of 208 inhabitants in 2017, due to topography with a focus on the Swiss Mittelland. 85% of the Swiss population lives in Cities and their areas of influence, 40% in the 5 large agglomerations of Zurich, Geneva, Basel, Bern and Lausanne.

Longer traffic jams, increased road repairs and missed transfers are not surprising when we hear that the number of kilometres travelled has doubled in the past 10 years. One of the best answers to improve this situation is a well-developed public transport system.

This needs well-coordinated and realistic time tables, and compact transfer points. So bus stops and tram nodes in the immediate neighbourhood of train stations and airports with their classic cabstands and parking garages.

Cities and municipalities are increasingly investing in high performance hubs where the means of transport can be changed. Depending on the location the hubs are supplemented by e-bikes and scooters or car-sharing parking spaces as well as shops for daily needs.

We had the opportunity to work on several special projects in excellent teams as structural engineers for roofs, which simply have to function as functional buildings and, thanks to their architecture, make the location recognizable. Our clients therefore like to speak of functional urban art - of urban identification points with quality of stay for our modern and increasingly mobile society.

2. The Projects

Our competition entries for the Bus Terminal Fellbach (D, 2005), the Bus Terminal in Hamburg Barmbek (D, 2012), the "Wölkli" in Aarau (CH, 2013), the City Train Station Ulm (D, 2014), the Mobility Hub in Backnang (D, 2017), the Station Square Goldau (CH, 2018) and the ongoing planning for the Bus Terminal in Sursee (CH, 2019-23) provide answers and make suggestions.

All projects are characterized by an encased construction and particularly sustainable surfaces that still look valuable even after years.

Figure 1: Bus Terminal Fellbach [D.Hartung]

Figure 2: Bus Terminal Hamburg Barmbek [archimage Meike Hansen]

Figure 3: Bus Terminal Aarau [Niklaus Spoerri Zürich]

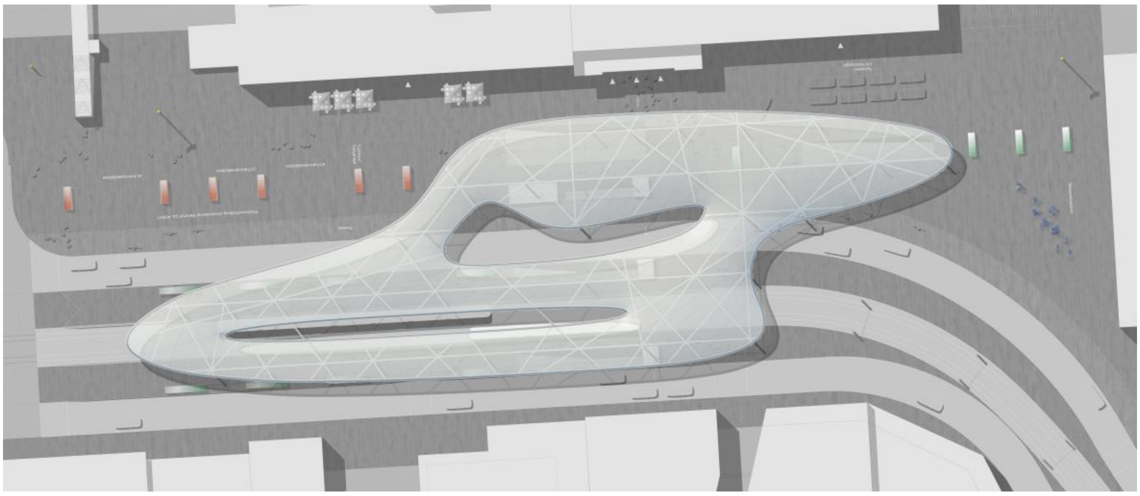


Figure 4: Transfer Hub Ulm [vielmo architekten GmbH]

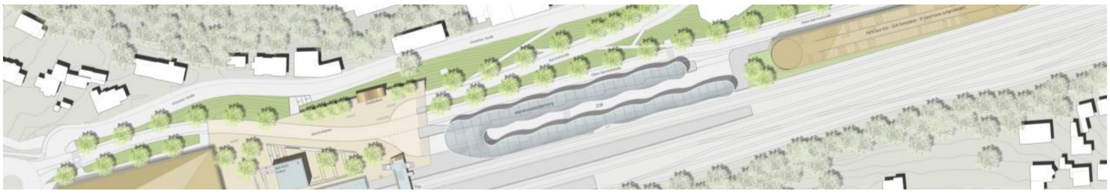


Figure 5: Mobilty Hub Backnang [Kienleplan GmbH]

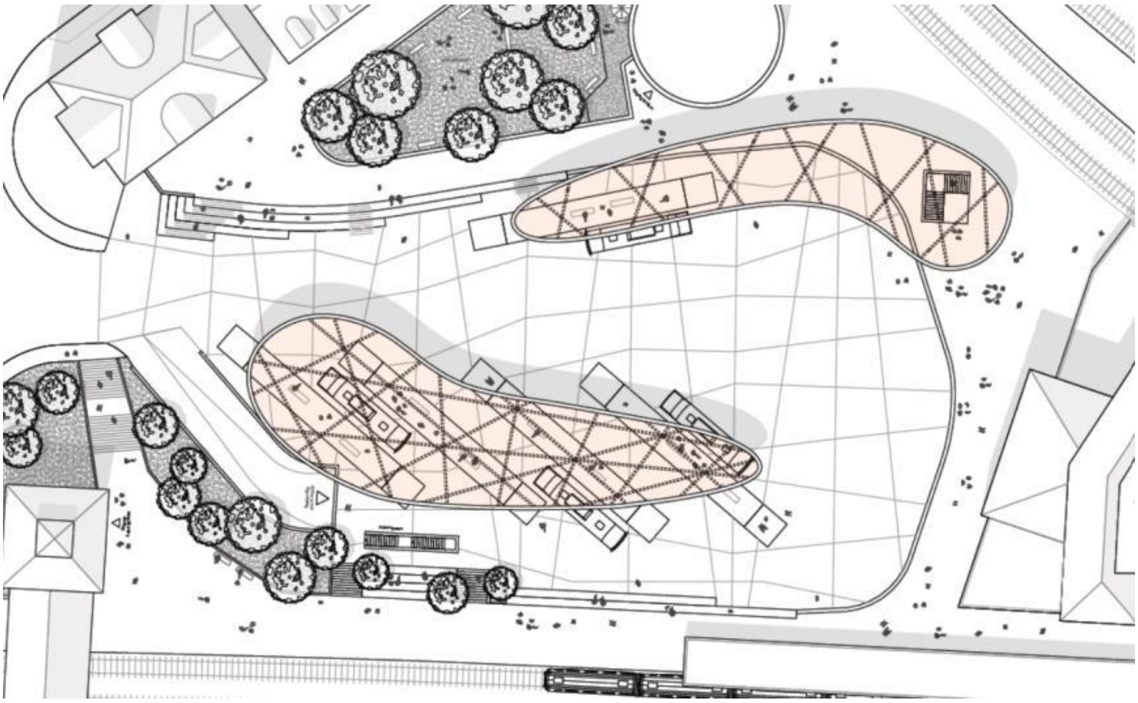


Figure 6: Station Square Goldau [suisseplan ingenieure AG]

Figure 7: Bus Terminal Sursee [OSMB Architekten GmbH]

3. Analysis

An analysis of roofs in public spaces shows that it is often forgotten that such buildings are rarely cleaned. The glazing and the colour-coated metal roofs are dirty, pigeon defence spikes stick to lattice girders in which paper cups, bird feathers and grey cobwebs collect.

The buildings only inadequately fulfil their intended task, because lack of care provokes negligent behaviour and the public places become more and more inhospitable.

It also shows that construction is often carried out with open profiles on which a lot of dirt is deposited and whose flanges offer pigeon's space to land and shit. As a result, these roofs often look neglected. It doesn't have to be like that.

4. Evolution of our encased structures

We therefore use materials that have less dirt adhesion. For example anodized aluminium, ETFE foil and fabric with laminated PTFE foil or PTFE-coated fabric. That is why we use round tube profiles instead of open profiles and, wherever possible, enclose the supporting structure completely with a smooth cover that does not offer pigeons a landing place.

We started with the bus roof in Fellbach in 2005. At that time we uses aluminium corrugated sheet on a steel frame. We got the chance of a lateral entry because our special proposal was only half as expensive as a solid roof. The foundation points were already given, which determined the position of the supports.

In our Hamburg Barmbek project, we designed long wing roofs with modular cushions, which we widened in the edge area so that the lighting with linear Fluorescent tubes could be integrated into the edge beams.

2013, with the Aarau bus station roof, we dared to use the ETFE large cushions technology, developed for Tropical Island, on horizontal surfaces. We planned a freely formed steel table and covered it with a pneumatic cover made of rope-reinforced ETFE foil.

In recent times we also used PTFE glass fabric for large pillows. The much higher strength enables perfect soft rounded roof surfaces.

5. Maintenance

Because our supporting structures are protected from dirt and the foils are almost self-cleaning, the structures remain clean for a long time even without maintenance. This is unique.

6. Corrosion protection

Because of the low additional costs for long-term corrosion protection, we demand the protection duration class "Very High" according to DIN EN 12944-5 as standard. That is for 25 years or longer. It takes little effort to convince the customer that this is the most sustainable way to invest his money. Wherever possible, stainless steel components are part of the standard configuration for exposed components such as ropes and rope connectors.

7. Sustainability

We too had to learn first that air supported envelopes do not cause high operating costs.

Our roof in Aarau is monitored in this regard. 1 SFR per square meter and year is charged for the power of the support air system, which dehumidifies the large pillow and inflates it with 300 Pascal in summer and up to 850 Pascal under snow. For this we have installed a circulating air system from Elnic GmbH, in which a closed air circuit is set up between the support air generator and the cushion roof. We only use exhaust air systems in exceptional cases, for example for temporary use.

8. "CLOUD-Effects" of transparent encased table-structures

Our clients and their users like this unusual and surprising "CLOUD-design" and the visual lightness. This results from an interaction of the structure and the cladding with the sun, with the colour of the sky and with artificial light in the night. Such roofs are never dark. They convey security and create a good and friendly atmosphere on site.

9. Perfect fit

Last but not least: We and our architect partners profit from the fact, that the table geometry can be freely adjusted and arranged to all organic footprints, parking bays or the curved lane of busses.

10. Outlook

The shown design language is of course not only suitable for mobility buildings but basically for all types of buildings in public spaces, where it is important that architecture creates identity. Such as the huge market place roof in Poznan (Poland). This one cushion roof from 2020/21 with cable supported ETFE-foil and a table structure is bigger than Aarau, which was the largest one cushion roof until now.

11. References

[1] Bus Terminal Aarau: Ingenieurbaukunst 2015, pages 70-79

[2] Bus Terminal Aarau: DBZ 12/2013, pages 28-35

[3] Bus station roof Hamburg-Barmbek: Stahlbaunachrichten 04/2013, pages 24-28.

[4] https://www.eda.admin.ch/aboutswitzerland.html

Applied Composite Materials
https://doi.org/10.1007/s10443-021-09941-8

Advanced 3D Textile Applications for the Building Envelope

Claudia Lüling[1] · Petra Rucker-Gramm[1] · Agnes Weilandt[1] · Johanna Beuscher[1] · Dominik Nagel[1] · Jens Schneider[2] · Andreas Maier[2] · Hans-Jürgen Bauder[3] · Timo Weimer[3]

Received: 13 May 2021 / Accepted: 9 July 2021

Abstract
Within the field of textile construction, textiles are traditionally used either as decorative elements in interior design or as flat textiles in tensile-stressed lightweight constructions (roofs, temporary buildings, etc.). Technical textiles made of glass or carbon fibers are now also used as steel substitutes in concrete construction. There, flat textiles are also used as lost formwork or shaping semi-finished products. Applications for 3D textiles and in particular spacer textiles have so far only been investigated as part of multilayer constructions in combination with other elements. Otherwise, there are no studies for their application potential in the roof and wall areas of buildings and as a starting structure for opaque and translucent components. The two research projects presented here, "ReFaTex" (adjustable spacer fabrics for solar shading devices) and "ge3TEX" (warp-knitted, woven and foamed spacer fabrics) illustrate for one thing the possibilities for using 3D textiles for the construction of movable and translucently variable solar protection elements in the building envelope. Otherwise they show how 3D textiles in combination with foamed materials can be transformed into opaque, lightweight, self-supporting and insulated wall and ceiling components in the building envelope. Both projects are designed experimentally and iteratively. The results are compared in a qualifying manner, the aim being not to quantify individual measured variables but to explore the development potential of textile construction for sustainable future components and to realize the first demonstrators. In the ReFaTex project, 1:1 demonstrators with different movement mechanisms for controlling the incidence of light were realized. In the ge3TEX project, 1:1 demonstrators made of three different textile and foam materials were added to form new single-origin composite components for ceiling elements. Both projects show the great application potential for 3D textiles in the construction industry.

Keywords Lightweight Architectural Design · 3D Textiles · Spacer Fabrics

✉ Claudia Lüling
clue@fb1.fra-uas.de

[1] Frankfurt University of Applied Sciences, Frankfurt 60318, Germany

[2] Institute of Structural Mechanics and Design, Technical University of Darmstadt, Darmstadt 64287, Germany

[3] German Institutes of Textile and Fiber Research Denkendorf, Denkendorf 73770, Germany

Published online: 15 October 2021

1 Introduction

Textile architecture is very often associated with tent structures. Design strategies as developed, for example, by Frei Otto [1] still dominate architectural thinking and discussions. These tent structures consist of single-layer textiles subjected to tensile stress, which only develop spatial qualities when combined with cables and compression bars. For some time now, a team of architects and engineers at Frankfurt UAS together with the DITF (German Institutes of Textile and Fiber Research Denkendorf) and other partners have been investigating in particular the new potential of multilayer, sandwich-like 3D textiles for building applications. Starting with the two main types of building element typologies—opaque wall and roof elements and transparent or translucent opening elements—one question focused on has been how to add value to 3D textile structures by combining them, for example, with foam. The aims of the accompanying “3dTEX” [2] and “ge3TEX” [3] projects are:

- to establish and improve fiber and foam materials in order to improve the structural and insulating behavior of the new composite of foam and fibers;
- to investigate appropriate textile technologies and geometries depending on the different applications in the building skin, e.g., wall and roof elements;
- to design and build lightweight, formactive building element demonstrators on a 1:1 scale.

The team is also exploring the specific, constructive-aesthetic possibilities for 3D textiles solar shading devices for partial transparent or translucent opening elements in “ReFaTex” [4]. The question to be answered is whether 3D textiles due to their individually adjustable material thickness offer spatially effective modification via still unexplored movement options with low energy input. Movement and time are thus integrated into the textile design as a fourth dimension. Accordingly, the focus is on movement mechanisms for opening and closing or for the control of viewing and incident light from spacer textiles with the aim of developing robust and low-maintenance components for facades. When closed, they can also temporarily reduce energy loss or the warming-up of the rooms behind them. Based on traditional solar protection systems such as shutters, venetian blinds and pleated blinds, the investigations with spacer fabrics show how these mechanisms when transferred to multi-layer textiles can open up the possibilities for daylight management control by moving the entire solar protection element (macro level) and activating the textile structure in itself and on the meso level.

2 Methodology

An empirical and experimental methodology was chosen for all of the research projects. At the beginning, experimental investigations with spacer textiles on a 1:1 basis were carried out and optimized by the research team in an iterative process involving student seminar papers and experimental student mock-ups (Fig. 1). The “SpacerFabric_Pavilon” showed for the first time the architectural potential of the combination of partially foamed 3D textiles, combined with the translucent and light-directing appearance of the 3D textile material. Based on this experience the research team followed two different paths: In terms of

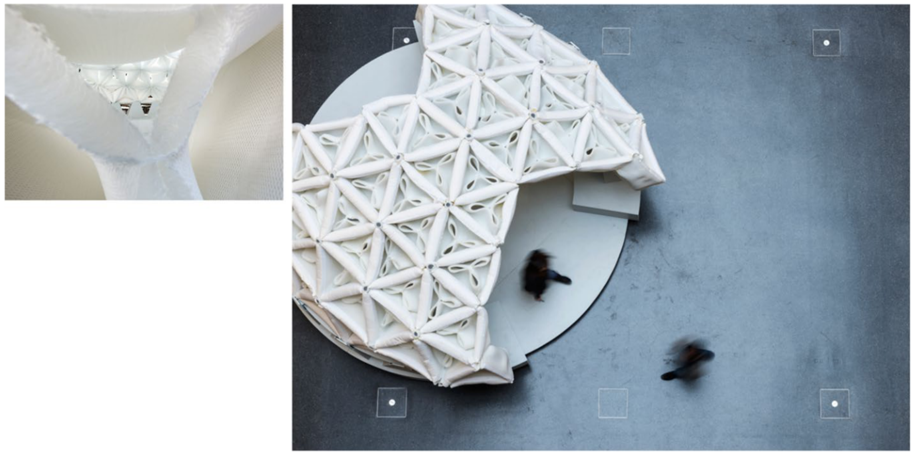


Fig. 1 Temporary pavilion made of foamed and folded spacer fabrics, “SpacerFabric_Pavilion”, left—view from the outside, right—view from the top. © Christoph Lison

solar-shading elements, the research project “ReFaTex” mainly involved the typological investigation of textile opening elements, based on existing solar shading devices. These traditional opening mechanisms were transferred to textile 3D geometries and modified accordingly in order to develop new options for controlling light incidence in buildings.

With regard to opaque building elements, the idea of foamed 3D textiles has so far been investigated in two projects, “3dTEX” and “ge3TEX”. In ge3TEX the full process was completed, from material formulations through to manufacturing techniques and the final design of building elements.Three material groups were selected together with the funding institution. The desired criteria were the possible fire resistance and recycling potential. Ultimately, new types of sustainable, foamed, textile composite components from one-single material group were identified:

- basalt fiber-based spacer fabrics in combination with cement foam;
- glass fiber-based spacer fabrics in combination with foamed glass from recycling resources (Fig. 2 shows the sequence of investigations carried out for this material group);
- spacer fabrics made from recycled PET-fibers in combination with PET-based particle foams, also from recycling material.

3 Results

3.1 3dTEX—Lightweight Wall Elements From Foamed Spacer Fabrics

In 3dTEX an initial understanding of the geometry of 3D textile structures was developed and concepts for relevant textile transformations tested, including for warp-knitted and woven 3D textiles. Figure 3 shows both textile technologies. On the left, a foamed warp-knitted spacer fabric becomes a framework-like wall structure with loadbearing and insulating areas. The unfoamed warp-knitted 3D textile is shown on the right side. The

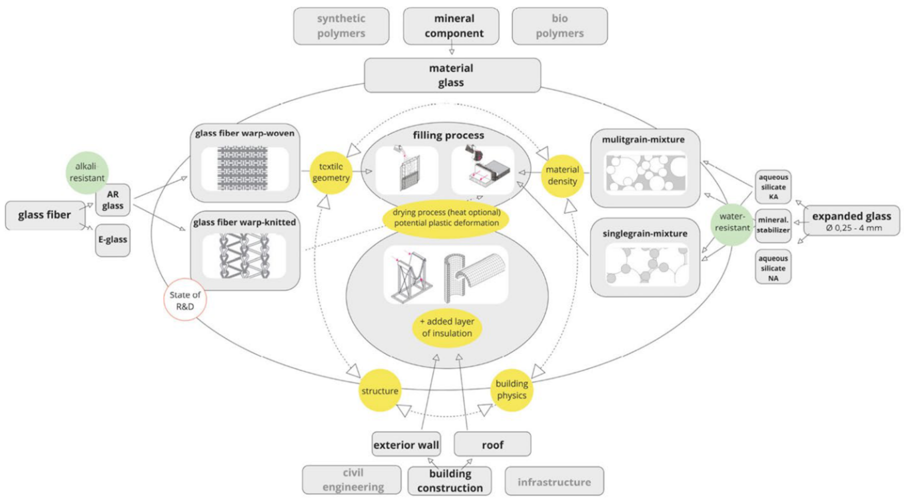


Fig. 2 Research methodology using the example of the development of foamed textiles made of AR glass textiles in combination with a filling of expanded glass with water glass. © Frankfurt UAS

focus was on the development of appropriate textile geometries for two-layer or three-layer textile elements, depending on the chosen textile technologies. Below right is an initial idea for a three-layer woven structure, designed and produced at the DITF [5]. The lower area of the three-layer fabric was foamed, while the upper area remained unfoamed for ventilation. In this way the three-layer textile was transformed into a ready-made, rear-ventilated, insulated wall element, able to absorb tensile and compressive forces at the same time. Bending tests and others were not conducted during this phase.

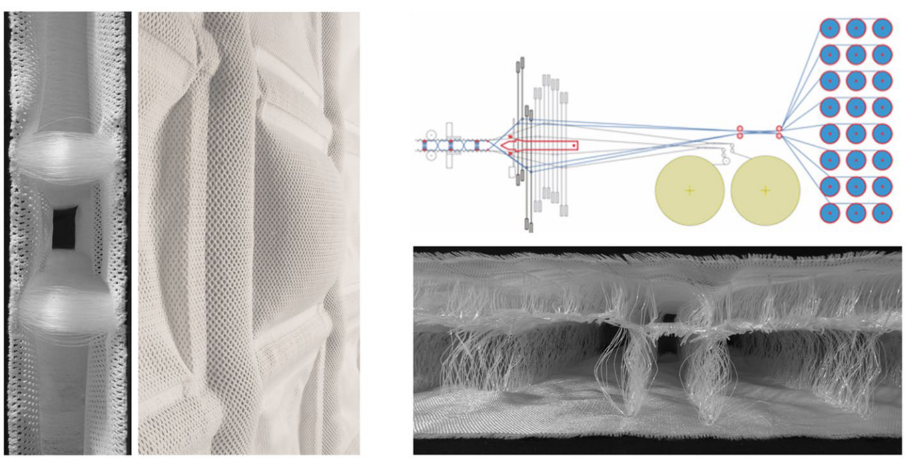


Fig. 3 The “3dTEX” research project (textile based, foamed wall elements): left side, warp-knitted and foamed spacer fabric; right side, spacer weaving machine with lancet technology and tangential withdrawal of the spacer threads from the creel and three-layer, woven spacer fabrics. © Frankfurt UAS and DITF

3.2 Ge3TEX—Warp-knitted, Woven and Foamed Spacer Fabrics for the Building Envelope

During the initial studies in 3dTEX, PU foams and PE fibers were used [6, 7]. The main objective was to identify the deformation behavior of the different spacer fabric types. Subsequently, further research was conducted in a follow-on project, ge3TEX, which focused on the enhanced materialization and sustainability of the new “fabricfoam” composite elements. High recycling potential and fire-safety building aspects were additional criteria. The decision was taken to use two mineral- and one polymer-based combination of fibers and foams, each from a single material background. The use of foamed materials such as cement foam, expanded glass and PET foams made from recycled material results in very different bonding properties with the corresponding basalt fibers, glass fibers and rPET fibers. It also results in different filling methods, which again led to the design of individual geometries for each demonstrator from each material group. Figure 4 shows the correlation between the parameters of textile 3D structures and the filling options. Ultimately, the aim is not the quantification of individual measured variables, but rather the comparison of components of different, single-origin material groups with the same functionalities and the implementation of the first demonstrators in order to develop new, formwork-free manufacturing techniques.

3.2.1 Basalt Fiber-based Spacer Fabrics in Combination with Cement Foam

A large number of tests had to be carried out to show whether the combination of foam and fibers had the potential to become a building component. Together with the industrial partner involved, the basalt rovings were individually poured into the cementitious foam matrix and tested for alkali resistance in accordance with DIN EN ISO 2062 and for damage in accordance with DIN EN 14,649 (SIC test). The manufacturer’s cementitious foam has a density of 180 kg/cbm. The adhesion of the individual rovings was also checked in pull-out tests. These rovings were cast into the cementitious foam according to the subsequent position of the pile threads between the cover layers and in the cementitious foam. In addition, the rovings were woven into single-layer textile fabrics. Their adhesion was investigated in peel-off tests according to the subsequent position of the cover layers on or next to the cement foam. Filling tests were only carried out with woven fabrics due to the rather fluid structure of the cement foam. Knitted fabrics are too porous and elastic to be used as lost formwork. Finally, first demonstrators were produced. To summarize:

- Special alkali-resistant and processable basalt rovings were developed for ge3TEX.
- The new rovings were used first of the first time all to produce spacer fabrics at the DITF, (Fig. 5).
- The adhesion of the new rovings to the cement foam was proven, but not the adhesion of the single-layer woven textile surfaces made from them; knitted textiles in contrast displayed excellent adhesion. As a consequence, the woven spacer fabrics were modified in such a way that loops formed on the inside of the spacer fabric leading to sufficient mechanical adhesion (Fig. 5).
- Due to the low density of the cement foam, it can only be used for insulation purposes. For lightweight, pressure- and tension-stable insulated components, geometries have been developed for initially single- and subsequently double-curved cushion structures made of basalt fabric. The cement foam cushion structure then serves as lost formwork

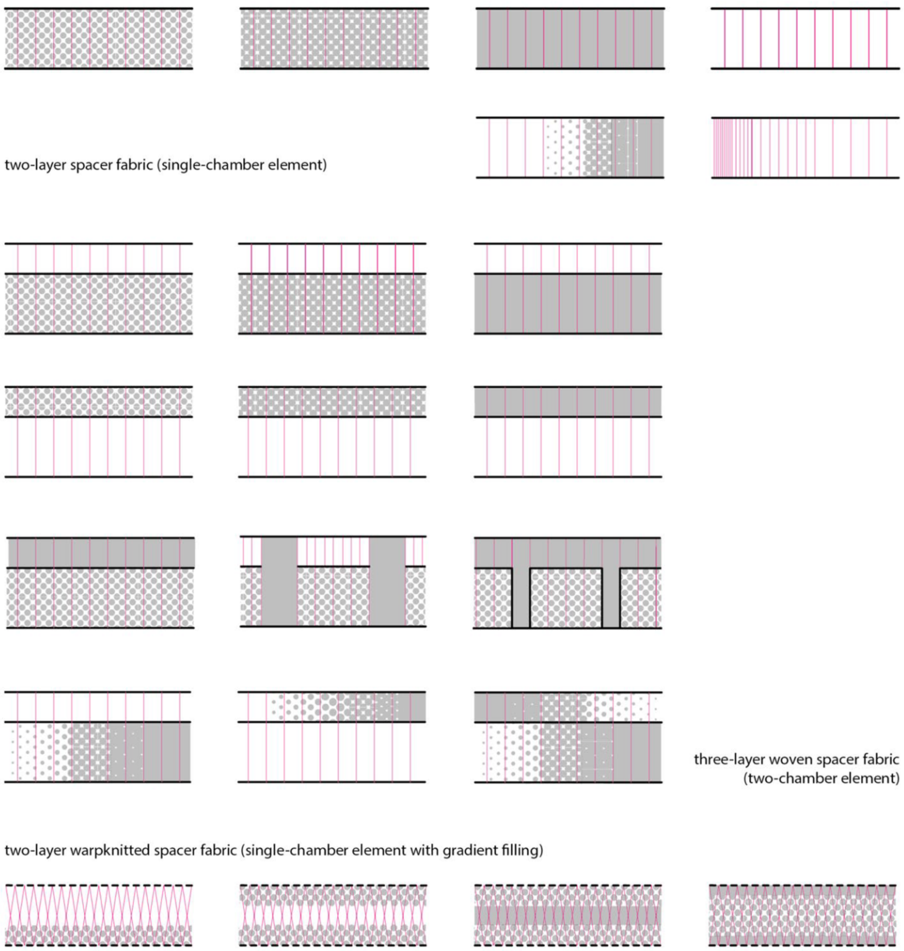


Fig. 4 Foamed spacer fabrics used as a "lost formwork": A formwork that stays in place, defines the surface quality but can additionally also be used for the transmission of tensile forces. © Frankfurt UAS

for an ultra-high performance top concrete layer. This results in a concrete-ribbed structure which is also supported horizontally underneath by the layer of filled basalt textile in the area of the crossing points. Production of the basalt spacer fabric includes reinforcement of the lower layer, which is strengthened in the area of tensile stresses (Fig. 6)

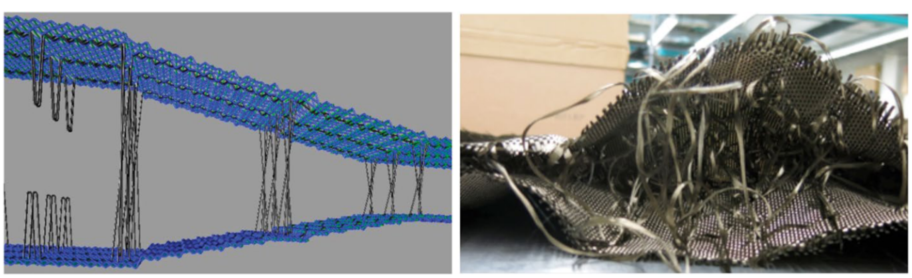


Fig. 5 Basalt fiber spacer fabric – woven. © Frankfurt UAS

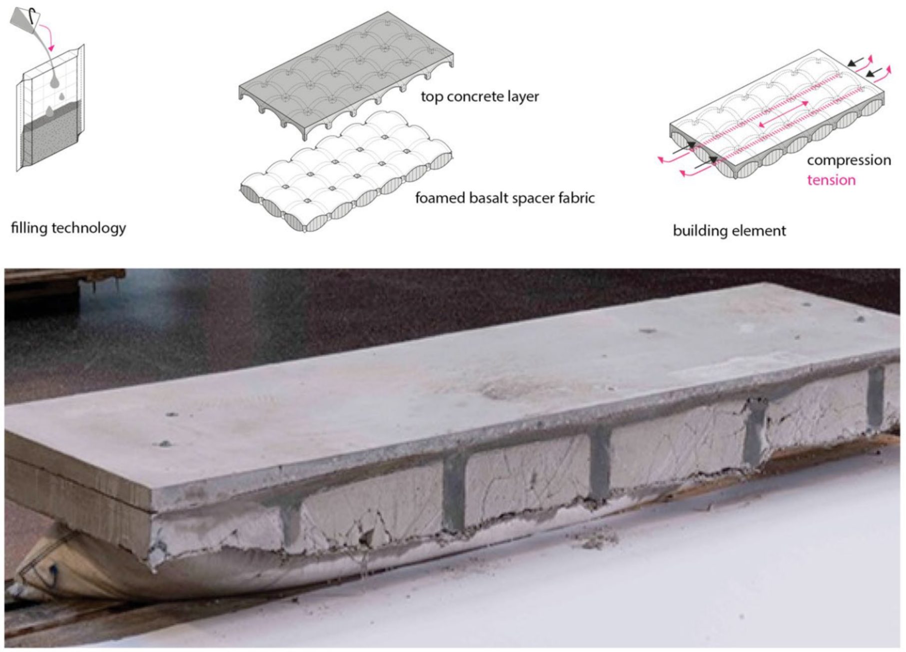


Fig. 6 First demonstrator: Formactive composite building component made of ultra-high performance concrete (UHPC), with lost insulation formwork made of basalt fiber spacer fabric, formed by a cement foam filling. © Frankfurt UAS

3.2.2 Glass Fiber-based Spacer Fabrics in Combination With Foamed Glass From Recycling Resources-

Expanded (foamed) glass made of recycled material can be bonded either by sintering (energy-intensive, in-situ unsuitable) or by using a suitable matrix to form a pore-based filler for filling spacer fabrics. Water glass was chosen as the development matrix, since the recycling objective for the new fabric-foam composite is the use of single-source materials. In contrast to the existing formulation for the cementitious foam, existing standard formulations for the production of waterproof expanded glass and water glass mixtures had to be tested and adapted for ge3TEX. The aim of the tests was to develop a processable, as light as possible, but equally pressure-stable expanded glass/water glass mixture—or to provide a number of formulations that are partially available for filling depending on the textile geometry and load case or insulation requirements (Fig. 4). The test series had the following parameters: density of the expanded glass granules, mixing ratio of the water glass and mineral hardener, drying temperature, drying time and waiting time until the mechanical and structural parameters are tested.

As with the basalt rovings, pull-out tests, peel-off tests and adhesive pull tests were also carried out with the glass rovings. In addition, the strength of the formulation was tested again after prolonged exposure to water. In contrast to the rather liquid, cementitious foam, the expanded/water glass matrix has a mortar-like structure. Filling tests were accordingly carried out with woven fabrics from the side and knitted fabrics over the cover layers. To summarize:

- Unlike with basalt rovings, all commercially-available E-glass rovings can be processed. Only two showed strong filamentation and are not suitable for the warp or for use as pile threads.
- The adhesion of single-layer fabrics made of AR glass was achieved satisfactorily through pre-treatment and impregnation of the fabric. It can be improved through mechanical adhesion as needed depending on the textile geometry of the top layers and the texturing of the pole threads.
- Structurally-dense mixtures as well as single-grain mixtures of expanded glass with different grain sizes were tested – the former on the assumption that they require less binder, because the spaces between them are filled by the smaller grains themselves rather than by the binder. The result shows that the optimized, dense mixture shows no added value in terms of strength and water glass content compared to a single-grain mixture of the same density.
- The mortar-like structure of the expanded water glass mixture enables warp-knitted spacer fabrics to be filled by squeegeeing the mixture over the cover surfaces (Fig. 7 - above center). The filling of an initial PE warp-knitted spacer fabric and subsequent drying over a mold showed very good results (Fig. 7—below right). Research

Fig. 7 Composite building component made of expanded glass in combination with lost formwork made of glass-fiber spacer fabric; below left - woven spacer fabric; below right - formactive warp-knitted spacer fabric. © Frankfurt UAS

is still underway into the production of warp-knitted spacer fabrics made of glass rovings. For reasons of processability it will probably not be possible to produce a stable pile yarn structure with the resilience needed for the squeegeeing process from glass rovings – a disadvantage as regards the desired monomateriality.

- For the first time, woven spacer fabrics made of AR glass were manufactured for the production of final demonstrators

3.2.3 rPET fibre-based spacer fabrics in combination wit rPET particle foam

Corporate partners were integrated into the project who manufacture space textiles from PET recyclate and PET particle foam from recyclate. Both products can also be returned to the recycling chain. Together with the partners, both the PET tapes and the selected PET particle foam were developed further (Fig. 8).

Two PET tape or strapping materials (standard material A and new material B with improved adhesion options) were tested as textiles A and textile B with standard particle foam A and with a likewise newly-developed particle foam B with greater expansion capacity. For the test, PET pouches were alternatively filled with unfoamed and pre-foamed beads and the expansion behavior and the fusion of the expanded beads with each other examined in different processes (oven, microwave, infrared, radio wave). In addition, two different adhesives were used to help the particles adhere to each other - a hybrid coating and an adhesive coating more appropriate for the planned mono-material. To summarize:

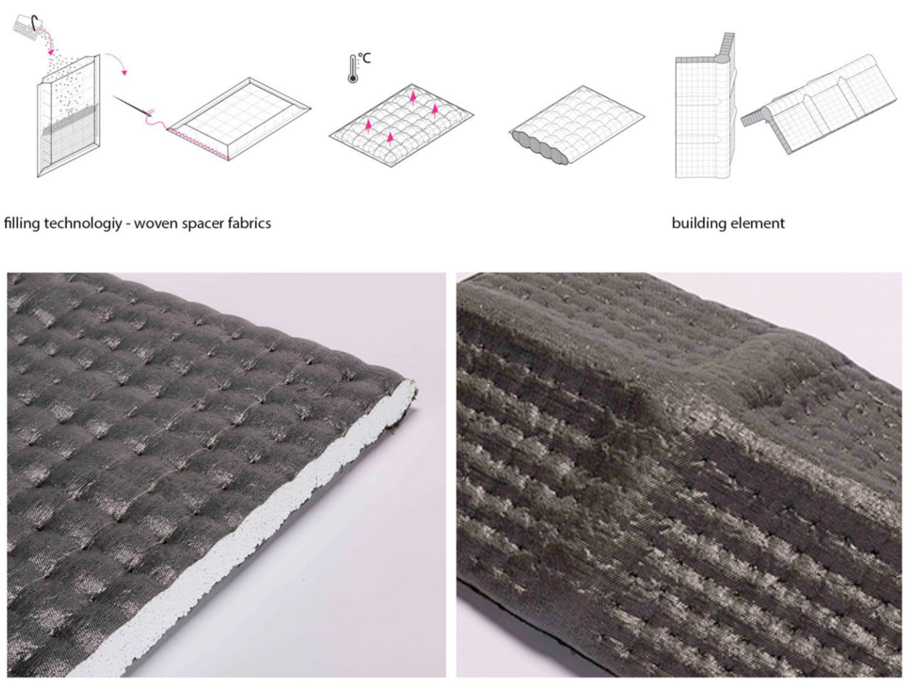


Fig. 8 Composite building component from expanded rPET particle foam in combination with lost formwork from rPET fiber—woven spacer fabric; left—planar element; right—self-foldable, formactive element. © Frankfurt UAS

- The shrinking behavior of the PET textile has a positive effect compared to the expanding particle foam. In various test series the optimal filling volume in relation to the shrinking textile volume was determined. All combinations of textiles A and B with beads A and B were tested. The new beads B are optimal, and the adhesion to the textile itself works best when using textile B.
- In further test series with and without pre-foaming, robust fusion of the foamed beads with each other was not achieved. Only by using an adhesive coating, which is added to the unfoamed beads, is it possible to produce a cut-resistant foam material from the foamed beads in a one-step process (Fig. 8).
- The particle foam expands in the spacer fabric. The textile thus serves as a shaping element for the expanding material; planar as well as formactive folded shapes were realized.

3.2.4 G3TEX - Results

In terms of opaque, self-supporting and insulating building components for the building envelope made from fabric-foam from three different material groups, Fig. 9 shows the advantages and disadvantages in each case and for the developed individual building elements, differentiated in terms of.

- recyclability
- weight
- global-warming impact

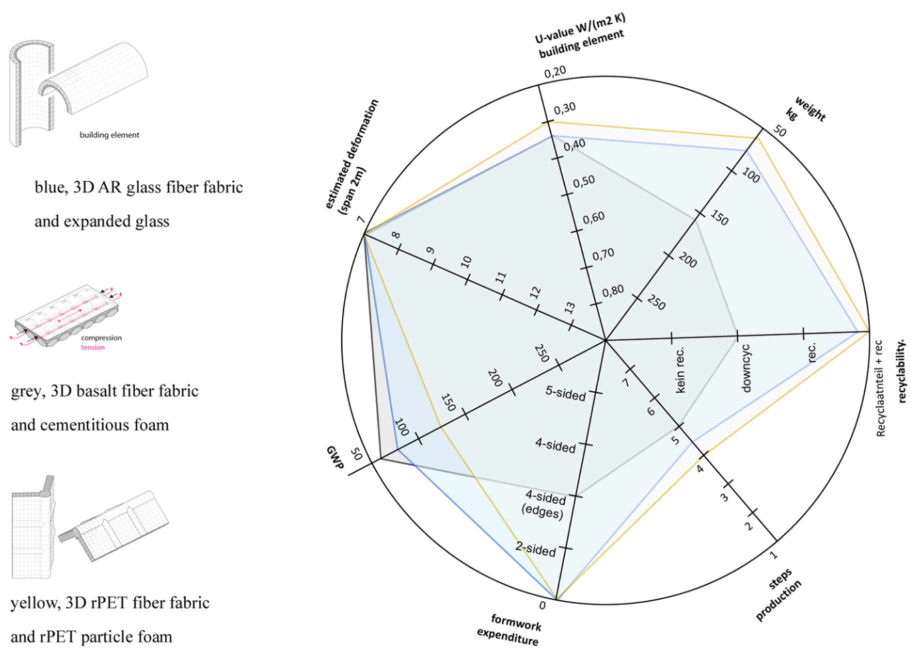


Fig. 9 Comparative presentation of 3D textile-based, foamed building elements, made of single-origin materials; all elements have comparable insulation values and deformation values. © Frankfurt UAS

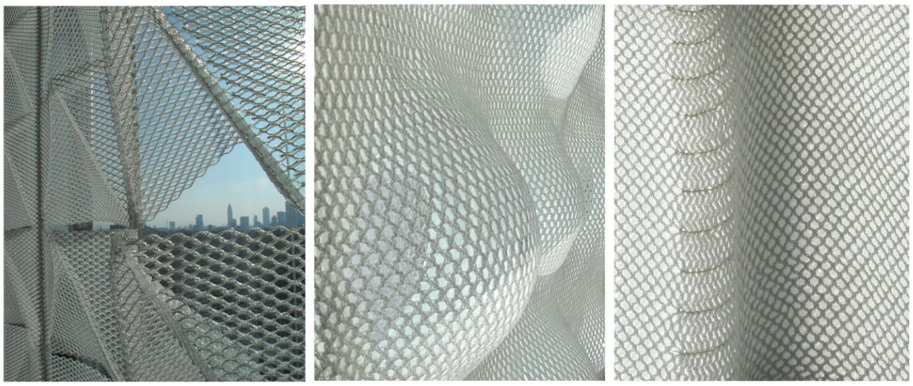


Fig. 10 ReFaTex—shading devices made of warp-knitted spacer fabrics. © Frankfurt UAS

Also part of the studies are lowest-possible transport volume, formwork dispensation, easy in-situ production and reduction of the process steps through use of highly functional semi-finished technical textiles. The results so far are very promising.

3.3 Adjustable 3D Textiles—ReFaTex

Ge3TEX looked into the question of opaque 3D textile-based, lightweight building elements for the building envelope. In contrast, the "ReFaTex" project deals with the most sensitive area of the outer skin of the building – the opening area. The object of the investigation is the extent to which multilayer textiles such as spacer textiles can be used as moveable, possibly adaptive solar protection and at the same time as temporary heat protection. The work is based on the "ReFaTex – reversibly foldable, energetically-effective 3D textiles in the building sector" research project, which focused on the production of ultralight and stable elements from spacer textiles in the facade area that were also to be foldable and, depending on requirements, opaque and partially translucent or transparent. In the course of the research, the term "foldable" was replaced by "movable" in order to comprehensively capture the dynamic potential of spacer textiles. The following figures show the different results from the project. Figure 10 shows first mock-ups, Figure 11 shows first concepts and Figure 12 shows how the strategies could be used in a building context.

With regard to light-directing and controllable transparency, three mechanisms with a high potential for further studies were identified—folding, bending/compressing and stretching. 3D

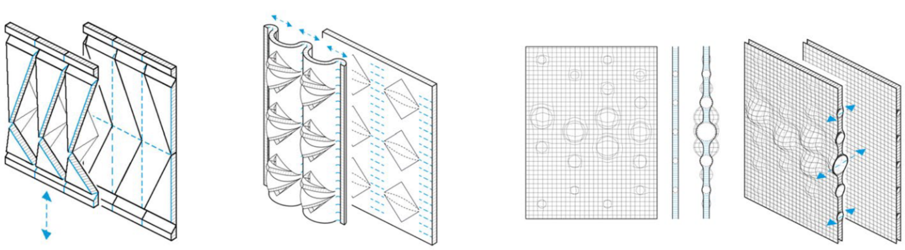


Fig. 11 ReFaTex, solar shading devices from spacer fabrics—folding, bending and stretching strategies to improve daylight control. © Frankfurt UAS

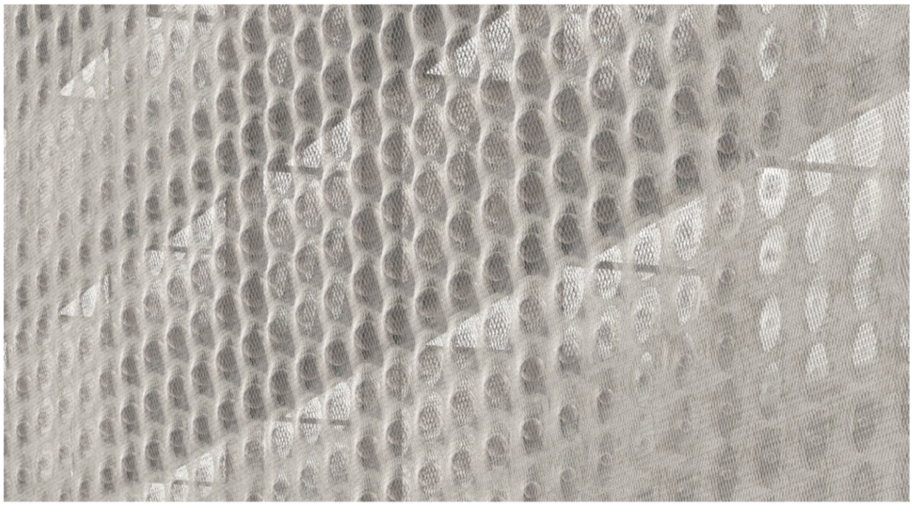


Fig. 12 ReFaTex, spacer textile, selectively stretched and in line with sunlight in real time with the help of internal pneumatic mechanisms. © Frankfurt UAS

textiles offer options for hingeless joints, achieved with partial incisions. New pleated structures can be created, which can also be used as external solar protection. To this end, the stability of the textile is increased by partial fillings as developed in Ge3TEX. Further applications are currently being developed for window shutters, lift-up shutters and folding shutters as well as pleated blinds in other geometries. Naturally, fabrics are subject to "soft wrinkling", and therefore the subject of bending mechanisms is valid. The elements realized so far appear to be much more "material"-like and softer than the folding structures. On the meso level, the bending of the spacer textiles results in the texture of the inner surface layer being automatically compressed or condensed. The bending movement can be used to selectively adjust areas with translucency (Fig. 10, right).

Fig. 13 6dTEX, 3D printing on 3D textiles, Frankfurt UAS together with ITA Aachen. © Frankfurt UAS

Consequently, on the macro level this means that the entire element must be correspondingly larger than the opening element. As a whole, the new elements resemble a thick, translucent curtain. Moreover, warp-knitted spacer fabrics can be stretched due to their mesh structure. Just as when the textiles are bent, the stretching movement changes the translucency. The elongation of individual, pile-thread-free textile areas perpendicularly to the cover surfaces was also investigated and resulted in a bubble-like solar shading device (Fig. 12). The next step is the development of a robust coating for all elements for cleaning reasons. All the systems are protected.

4 Conclusions

Spacer fabrics offer advanced 3D textile applications for the building envelope. Frankfurt UAS's projects demonstrate new options for sustainable, lightweight and highly functional building elements for the future. Further tests must be undertaken to improve the mechanical and physical properties of the composite materials and thus the functionality of the new composite components, depending on the individual application. In addition, further material combinations of fibers and foams will be investigated at Frankfurt UAS, for example based on renewable raw materials. With regard to ReFaTex, the light transmission values of the different shading devices are still being measured and support from the textile industry is needed to help with the different surface geometries of the spacer fabrics. In the "6dTEX—3D printing on 3D Textiles" follow-up project (Fig. 13), further investigations will be made with the aim of realizing "Architecture Fully Fashioned" in the future. Fully fashioned refers to a textile production technology in which all the parts of an item of clothing are produced in one integrated production process, so that it is ready to wear the moment it leaves the machine. Fully fashioned in an architectural sense implies a highly prefabricated textile lightweight envelope with minimal installation work on the building site.

Acknowledgements This paper and the research behind it would not have been possible without the exceptional support of the "Zukunft Bau Forschungsförderung" of the Federal Ministry of the Interior, Building and Community. It also would not have been possible without the enthusiasm, knowledge and attention of my colleagues at Frankfurt UAS including Prof. Dr.-Ing. Petra Rucker-Gramm, and the Laboratory for Building Materials, Building Physics and Structural Conservation including Dominik Nagel, my colleague Prof. Dr.-Ing. Agnes Weilandt, our research assistants, in particular Johanna Beuscher, and all the students who helped us. Last but not least, my thanks go to the German Institutes of Textile and Fiber Research Denkendorf including Dr. Hans-Jürgen Bauder and his team, and the Technical University of Darmstadt including Prof. Dr.-Ing. Jens Schneider and his research team, in particular Andreas Maier. Furthermore, the work would not have been possible without the extraordinary support of our many industry partners, to whom we once again wish to express our gratitude.

Funding Open Access funding enabled and organized by Projekt DEAL. "3dTEX" and "Ge3TEX", Federal Ministry of the Interior, Building and Community, Germany "ReFaTex", IFOFO funding, State Chancellery of Hessen, Germany.

References

1. Meissner, I.: Frei Otto - A life of research, construction and inspiration. DETAIL, Inst. für Internat Architektur-Dokumentation (2015)
2. Lüling, C., Richter, I.: Architecture Fully Fashioned - Exploration of foamed spacer fabrics for textile based building skins. J. Facade Des. Eng. **5**, 77–92 (2017) https://doi.org/10.7480/jfde.2017.1.1526
3. Lüling, C., Rucker-Gramm, P., Weilandt A., Beuscher, J., Nagel, D., Schneider, J., Maier, A., Bauder, H.-J., Weimer, T.: Ge3TEX – Multifunctional Monomaterials Made from Foamed Glass-, Basalt- or PET-based 3D Textiles. Powerskin Conference Proceedings S. 37–51 (2021)
4. Lüling C., Beuscher, J.: 4dTEX – Exploration of Movement Mechanisms for 3D-Textiles Used as Solar Shading Devices. Powerskin Conference Proceedings S. 159–172 (2019)
5. Bauder, H.J., Wolfrum, J., Gresser, G.: Entwicklung von textilen Mehrlagenstrukturen mit optimierten Fachwerkkonstruktionen für mehrfach gekrümmte Bauteile. IGF. 17409 (2015)
6. Schäfer, K., Nestler, D., Jahn, K., Jentzsch, H., Kroll, L.: Lightweight potential of 3D endless fiber reinforcement of polyurethane foam cores with spacer fabrics in hybrid sandwich structures with fiber reinforced thermoplastic facings. In: Hausmann, J.M. (ed.) Key Engineering Materials (2019)
7. Schäfer, K.; Valentin, S.; Meier, B.; Roth, I.; Helbig, F.:Verbundvergleich von hart mit weich – Leistungssteigerung rigider PUR-Hartschäume durch weichelastische 3D-Gewirke Kettenwirk-Praxis - Technical Textiles (2014)

Do we need technical specifications for membrane structures?

Bernd Stimpfle
Board of Directors, TensiNet Association - International non-profit association
Ternat (Brussels), Belgium, info@tensinet.com, bernd.stimpfle@form-tl.de

Abstract

The development of a common European code for membrane structures is in progress. Does this process improve the quality of our structures? Are there benefits for all of us?

This paper presents the progress of the Eurocode for membrane structures, and shows with examples the importance to include the membrane structures from the beginning in the design process.

Keywords: standardization, membrane structures, integrated design

1. Introduction

Few national design codes for membrane structures are available today. They cover specific types, such as air halls, temporary structures or mechanically tensioned structures with specific constraints. Since long time discussions are going on, how to create a commonly agreed design code. It should provide the common practice on verification, design approach and quality standards.

Starting with the European project TensiNet [1] a first step has been done into that direction. In 2008 the TensiNet organisation, the follow-up network that has been established after the European project, implemented a working group Specifications and Eurocode. This resulted in the standardisation committee CEN/TC 250 WG5, formed in 2010 with the target to elaborate an Eurocode on membrane structures.

This working group has published in 2016 a SaP (science and policy) report [2], which is a background document of the actual state of the art in different countries, and is giving an outlook on a future Eurocode. Now the next step towards this Eurocode for membrane structures is in progress, the technical specification CEN TS 19102. We have the final document is actually being reviewed by the working group and the different mirror groups. In 2022 it should be hand in to the CEN for formal vote and publication.

Figure 1: Eurocode Visual for the TS “Design of membrane structures” [© European Union, 2021]

2. Reasons for a common standard

The experts in the field are capable to develop membrane projects without an Eurocode. So why should they work on the new standard, and at the same time help their competitors?

There are many different reasons and opinions. Probably as many as we have participants in that field.

- All agree on the fact that this helps to increase the market.
- We all want to have our technology seen as an established building technology and not only a niche market with high risk.
- With harmonised safety levels, and commonly agreed quality standards, we improve the quality of our industry and we avoid doubts of our clients.
- Once all players respect the same high-quality standards this will result in a fair competition.
- By being involved in this standardisation process, one can influence the result and later be satisfied with the final result.

3. Understanding membrane structures

Membranes are often seen as cladding, treated as add-ons applied to the building or the structure. But this is neglecting at the same time beneficial and unfavourable impacts, as shown with the following examples:

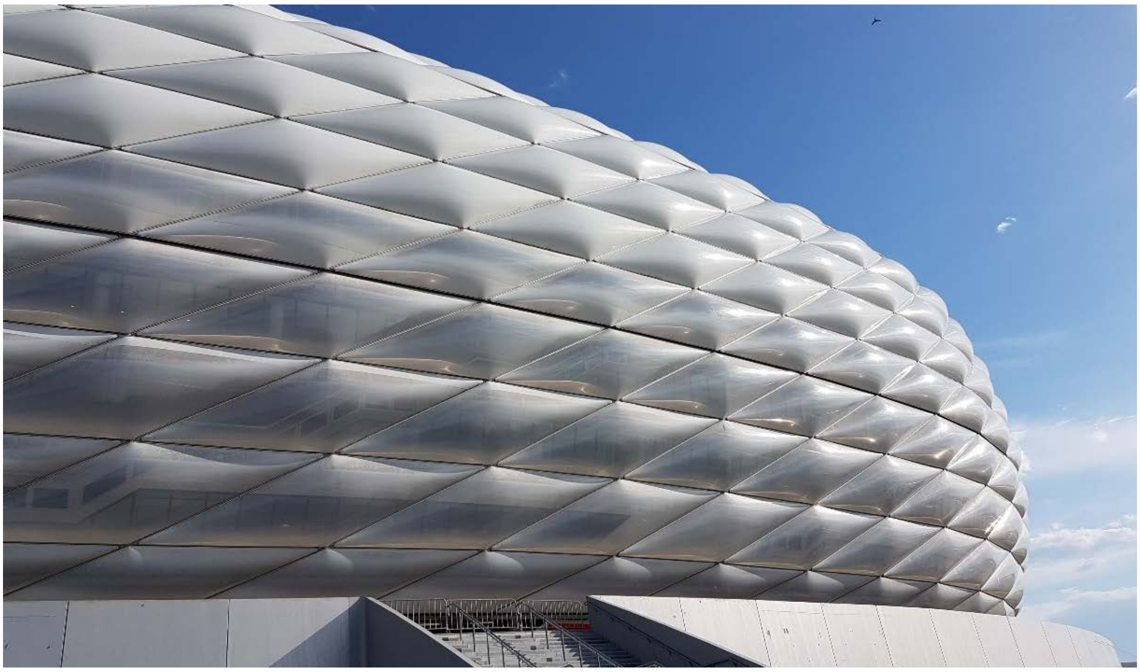


Figure 2: Allianz Arena [formTL]

The roof structure of the Allianz Arena for example has been designed without considering the ETFE façade. Just the self-weight has been considered. This resulted in another 50 % of steel weight that was required to realize the secondary structure. With an integrated design we suppose that only a small amount of additional steel would have been needed to apply the cushions on the structure.

Furthermore, the primary structure of seating bowl and roof has been subdivided with expansion joints in order to minimize constraints due to thermal expansion. Due to the long cantilevers of the roof, one can easily imagine the large deformation in these joints. The ETFE envelope had to be realised as a continuous surface. Therefore, in the roof area the secondary structure is sitting on rather long pin jointed struts, compensating the differential movement of the primary structure underneath. Large spring elements brace the ETFE grid, and keep the constraints acceptable low. In the façade each rhombic cushion has flexible corners and compensating the deformation of the bowl redistributed over the full length of the façade. Knowing this from the beginning, it would have been an easy task to provide a continuous primary structure, and reduce the cost of the façade.

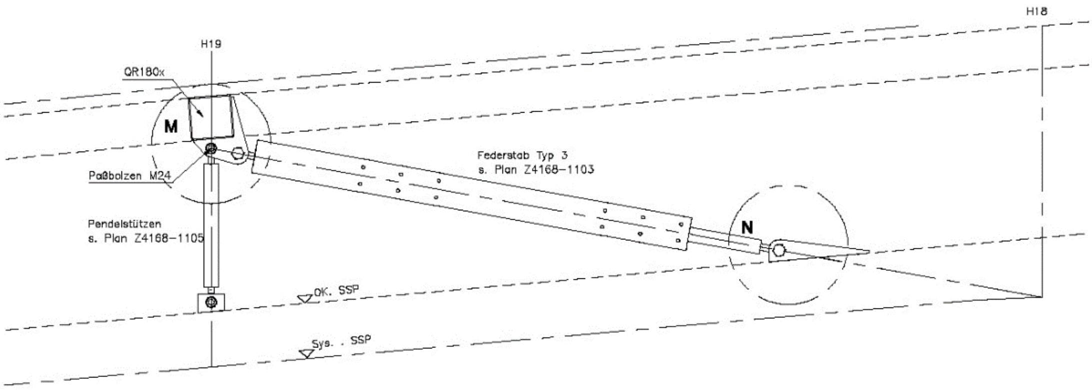


Figure 3: upstand with spring packet [formTL]

The same happened to the Unilever façade, which has been treated as a simple façade too, which was supposed to transmit just the external forces due to wind to each slab, and the self-weight of the façade in one slab. Due to the diagonal orientation of the façade the self-weight creates a bending moment, which leads to much higher vertical reactions loads.

Therefore, it was necessary to build stiff and heavy steel frames to couple the high tensile forces resulting from the single layer ETFE façade. Difficult built-in parts, instead of the initially foreseen resin anchors, were needed to fix the façade in the prestressed concrete slabs.

Figure 4: Unilever Hamburg, ETFE foil façade [formTL]

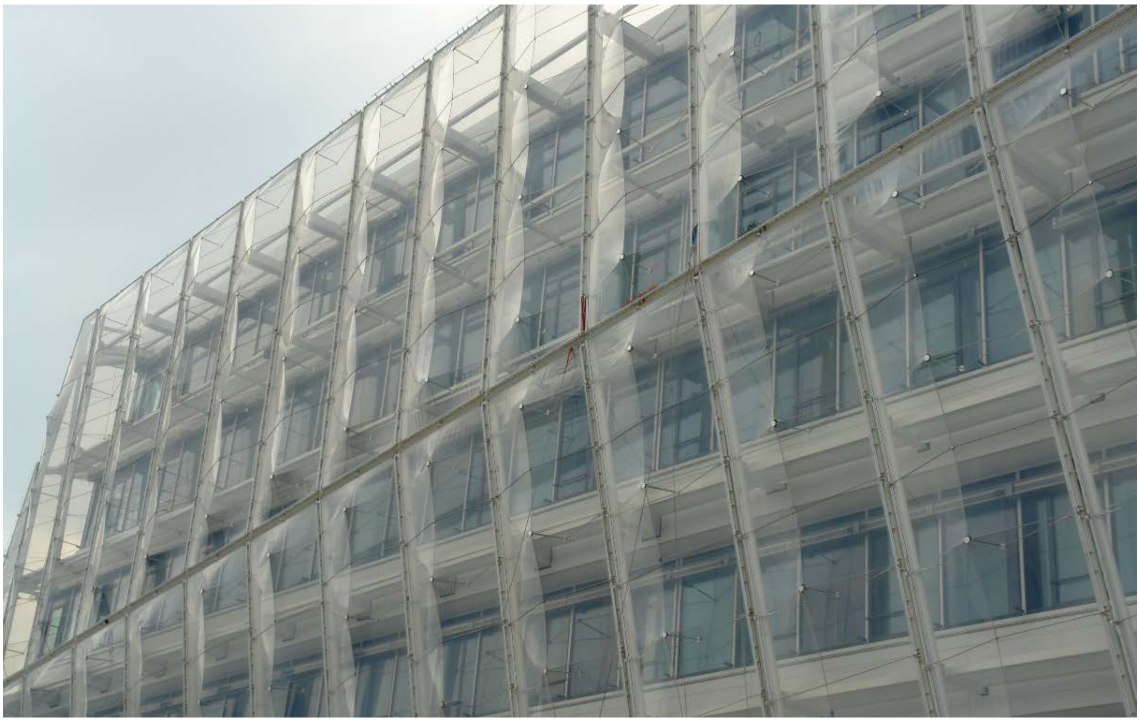


Figure 5: steel frames and connection to the building [formTL]

The proof engineer of the Dresden Castle ETFE roof answered to the engineers when they sent the analysis of the cushions: “I do not check the roof tiles either”

Figure 6: Dresden Castle, canopy of the small courtyard [Jürgen Lösel]

Figure 7: steel grid with cushion cladding [formTL]

4. Integrated design must be the future

Integrated design is elementary in our business. Neglecting this will never end in excellent and economic structures.

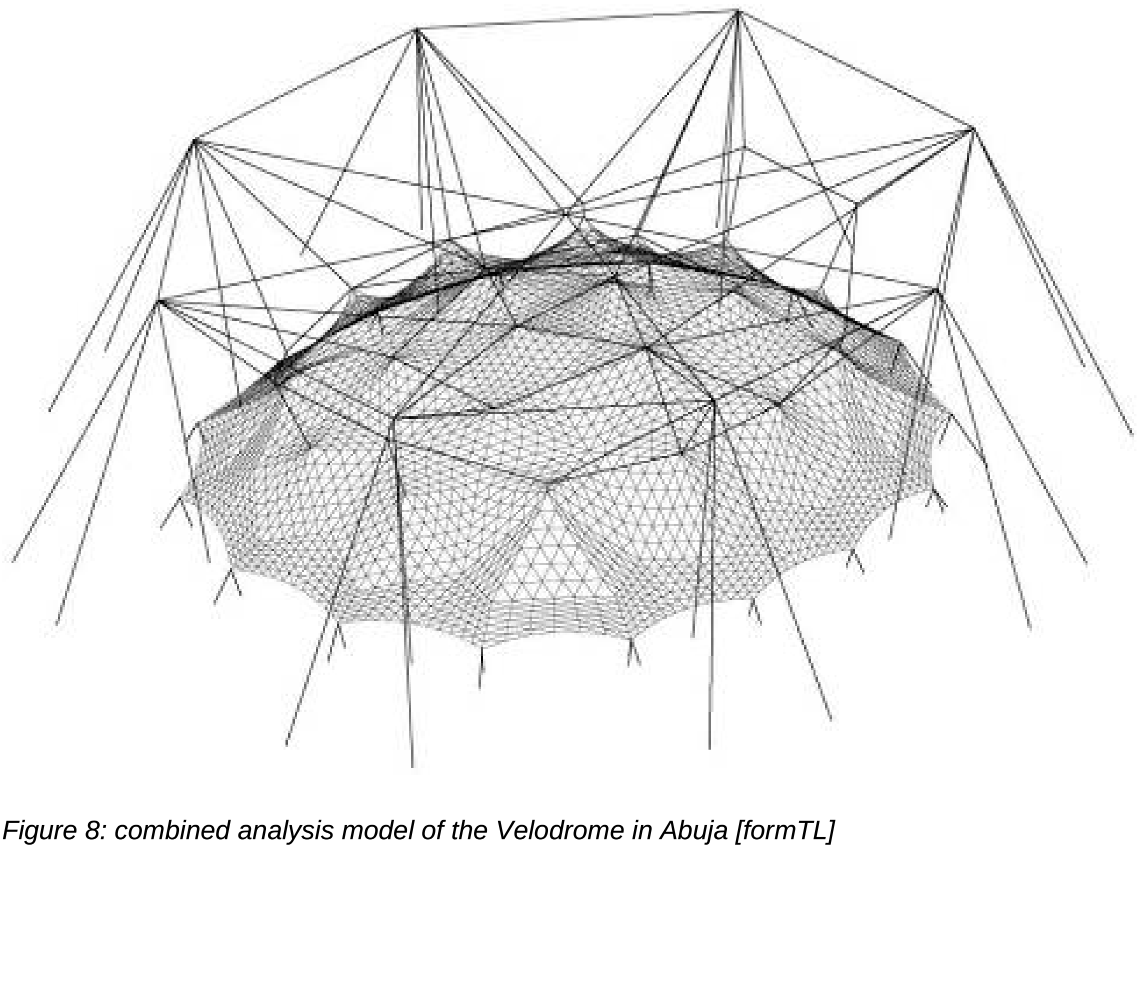


Figure 8: combined analysis model of the Velodrome in Abuja [formTL]

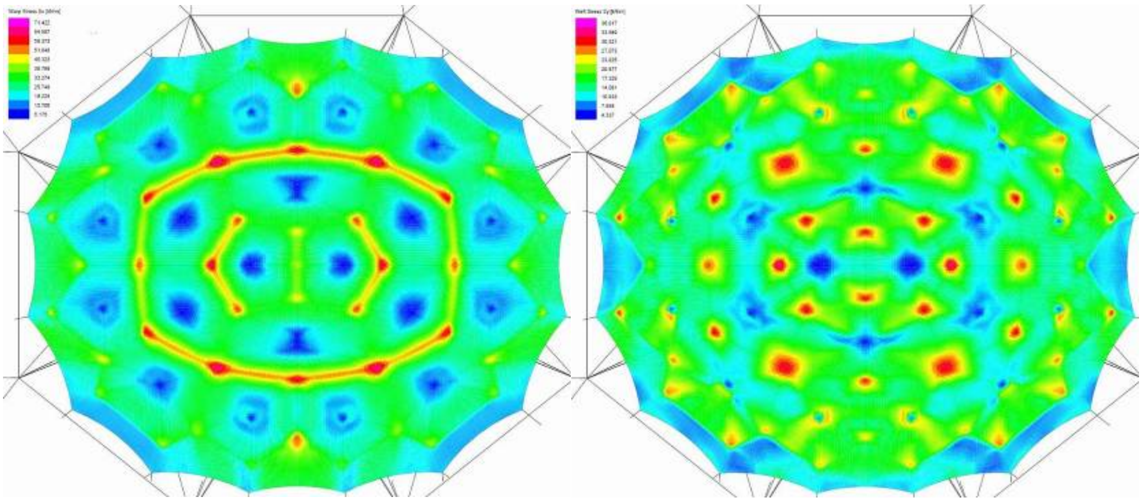


Figure 9: stress results example [formTL]

Large deformation of membrane structures helps to redistribute the loads within the structure, and reduce local stress peaks. The steel and cable can be used much more efficiently, and the stress results show up much more homogeneous and realistic.

5. Conclusion

As mentioned here, there are different opinions for an Eurocode, so are for example some interested in an increased market, and wouldn‘t care about safety levels, and others are mainly interested to minimise the administration process for approval.

The ongoing standardisation process is needed to keep and to improve the quality of our structures. It helps that others treat our business with the required seriousness to the benefit of all.

If we contribute to an Eurocode for structural membranes, we take part in the decision process, and will get finally a document that fits with our needs.

6. References

[1] European Design Guide for Tensile Surface Structures, Forster, B., Mollaert, M. (eds), TensiNet Association, 2004.

[2] Prospect for European Guidance for the Structural Design of Tensile Membrane Structures, Support to the implementation, harmonization and further development of the Eurocodes, JRC Science and Policy Report, European Commission, Joint Research Centre, Editors: M. Mollaert, S. Dimova, A. Pinto, St. Denton, EUR 25400 EN, European Union, 2016

Analytical calculation of membranes and foils for building skins

Jürgen Holl, Dieter Ströbel
Easy Software Development, technet GmbH
Stuttgart, Germany, juergen.holl@technet-gmbh.com

Abstract

A computer model is a discrete mathematical representation of the reality. It should enable the most accurate and complete formulation of a structure. If high-quality results must be achieved, software products must meet these requirements. Various methods and tools for generating accurate and complete models are shown. Fast and efficient form finding procedures are explained more detailed.

Static analysis is a challenge in case of a holistic formulation. The membrane/foil material behavior must be applied correctly, usually it is described by 4 values (E-modulus in warp and weft-direction, the crimp-stiffness and the shear modulus). Furthermore, the structure must be calculated in a hybrid system (membrane together with steel). In case of pneumatic systems, the statics can be done under 3 possible constraints: volume, internal pressure or gas-law (product of volume and inner pressure remain constant) are shown.

Cutting pattern theories are mentioned briefly, here we put the focus on flattening theories as it is the main part of the cutting pattern generation of prestressed double curved surfaces.

After the theoretical part, examples for form finding and cutting pattern generation of large pneumatic multi-layer ETFE cushion projects are described. The procedure for a parameterized automatic calculation is explained in more detail using the examples.

Keywords: Form finding, Statics, Cutting Patterns, Membrane, Foil

1. Introduction

Today, computer models play an important role in the calculation of textile membrane and foil structures. To be able to derive high-quality results from a model, the software used must enable the most accurate and complete description of a structure.

A great advantage of computer models is the possibility to perform a holistic calculation. Holistic in this context means that a complete model is analyzed under external loadings by taking into consideration any boundary condition. Computer models can also be used to automate processes. This can greatly accelerate the working cycle, especially for large structures.

Even though today's software tools offer considerable modelling possibilities, the user should always bear in mind that a computer model does not represent the exact reality and is always a partial and abstract view of reality.

2. Form finding

In a conventional design the architect fixes the real geometry on a drawing board. This procedure does not work for textile membrane and foil structures. This is not possible with respect to pre-stressed lightweight structures because internal forces or stresses and the surface geometry are not independent of each other. Therefore, when the usual design procedure is not possible, a form finding process is needed.

The form finding process can be described as the search for a geometry with ideal force flow and a favorable distribution of membrane stresses, considering aesthetic and constructional aspects.

For the form finding process you have in principle 2 possibilities. Either one builds physical models e.g. from nylon, soap skin, mesh, etc. or one uses analytical form finding methods.

Figure 1: Form finding with physical and computer model

The physical model has limitations regarding fast changes in the boundary conditions. The biggest problem, however, is the problem of scale: Inaccuracies in the model multiply with the scale of the model when transferred to reality, cutting patterns for textile membranes and cable lengths can generally not be derived from the physical models. Therefore, from the mid-1970s onwards, more and more analytical methods were used.

2.1 Analytical form finding

Analytical form finding theories are finite element methods. The surfaces are divided into several small finite elements as triangles for example. Most software programs use either the linear force density method or the nonlinear dynamic relaxation method. The force density method is a mathematical strategy for solving the equations of equilibrium for any type of cable network, without requiring any initial coordinates of the structure. The ratio of internal force to stressed length is defined as force density and assumed to be known. Thus, one obtains a linear system of equations which can be solved in one step without approximate values. Initially, the force density method was developed for cable nets, later extended to membranes and foils.

During the design process, the user must first specify the support points and their connections. Then, a first figure of equilibrium can be found by specifying the mesh direction and the magnitude of the prestress. By varying the initial values (mesh direction, prestress), the support definition (selective by point, linear as cable or arc, areal as internal pressure) and the arrangement of the boundary lines (flexible or rigid), the designer can vary the shape according to his ideas. In the case of pneumatic structures, the internal pressure or volume is used as an additional forming parameter.

2.2 Structural behavior of membranes and foils

Membranes and foils have a special structural behavior. The material is flexible and only tensile- (and shear-) stresses can be carried. We must use the membrane in a way that loads can be transferred only by tensile forces. This can be achieved by a double curved geometry and the introduction of prestress. Whatever the structural configuration, we need forms with double curvature to resist the applied loads. This can be of two types:

The surface of mechanically pre-stressed membranes is anticlastic doubly curved. For these types of surfaces an initial stiffness exists, all points can carry downward forces (e.g. snow) as well as upward forces (e.g. wind suction).

Surfaces of pneumatically pre-stressed membranes are synclastic doubly curved, pressure differences are used to introduce the pre-stress. The pneumatically stressed surface carries snow loads by reducing the membrane stress and increasing the internal pressure, while we find the opposite situation for wind suction.

Figure 2: Mechanically (left) and pneumatically (right) pre-stressed structures

3. Statics

A static calculation for membranes and foils is geometrically nonlinear. We need material properties for all elements and its nondeformed geometry. The nondeformed geometry of a cable element for instance is the unstressed length of this cable. Next, we need the external loads and in case of a pneumatic structure the internal pressure or volume information. After the form finding procedure a geometry is available and statics can be performed.

In contrast to foils, whose material properties are isotropic, orthotropic material properties must be applied to textile membranes. With isotropic material, the stiffness is the same in all directions or can be assumed to be the same. An orthotropic material has a special directional dependency in 2 perpendicular directions. In these directions there are different force-strain behaviors. The orthotropic directions are not independent of each other if the membrane crimp stiffness is different from 0.

In our software we use an extended material law. The stresses in warp and weft direction and the shear stresses are calculated as follows:

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_u \\ \sigma_v \\ \tau \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & 0 \\ m_{21} & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_u \\ \varepsilon_v \\ \Delta\alpha \end{bmatrix} \qquad (3\text{-}1)$$

$$m_{12} = m_{21}$$

with:

σ_u	Stress in warp direction
σ_v	Stress in weft direction
τ	Shear stress
m_{12}	Membrane crimp stiffness
m_{11}	Membrane stiffness in 1000
m_{22}	Membrane stiffness in 2000
m_{33}	Membrane shear stiffness
ε_u	Strain in warp
ε_v	Strain in weft
$\Delta\alpha$	Shear deformation

In addition to the stresses in warp and weft direction, the shear stress can be calculated if the shear stiffness is introduced as material value.

In the case of pneumatic structures, additional conditions must be observed: While in mechanically tensioned structures the loads do not change their size and direction during the loading process, this is different in pneumatically tensioned structures. The loading (magnitude or direction) does depend on the displacements of the model, the load vector must be set up based on the current displacements.

Furthermore, it is important for a realistic behavior of the calculation model that the software used offers appropriate possibilities. We recommend 4 calculation methods for the static calculation of pneumatic structures:

1. Given internal pressure p (snow)
2. Given volume V (water)
3. Given product $p{\cdot}V$ (Boyle-Mariotte, for example wind)
4. Given product $\frac{p{\cdot}V}{T}$ (General gas equation, consideration of temperature)

The third mode (consideration of gas-laws) enables the realistic behavior of the internal pressure. This mode is important in case of e.g. fast wind gusts. Here the pump systems cannot update the inner pressure in the short time. We can see it as a closed system and by considering the temperature as constant we get the gas law of Boyle and Mariotte $p{\cdot}V{=}const$ in this case. Only if the gas law is fulfilled the membrane stresses get the correct size. Mode 4 also considers the temperature, the principle itself is the same as mode 3.

The modes can be used e.g. as follows:

1. An air hall under snow-loading (a specific internal pressure is set to resist the snow-loads)
2. A membrane filled with an incompressible fluid (water-bag) and
3. A pneumatic cushion loaded by a fast wind-gust; here, the gas law ($p{\cdot}V{=}const$) is valid.
4. A pneumatic cushion loaded by a fast wind-gust; here, the gas law ($\frac{p{\cdot}V}{T}{=}const$) is valid.

To get correct results software packages should consider these effects.

4. Holistic calculation

To obtain the most realistic values for the static behavior of a membrane structure a computer model should enable the most accurate and complete formulation of a structure. With the next two sections we would like to point out special aspects in the calculation of prestressed membrane and foil structures combined with bending stiff primary structures.

4.1 Comparison - separated systems and combined systems

In membrane engineering often the membrane system and the primary steel structure are calculated in separated systems by loading the steel elements with the reaction forces of the pneumatic membrane which was fixed at its boundaries in a first calculation step. This procedure is wrong with respect to form finding and statics. Separation is only allowed if the deflections are very small and this is never the case for membrane structures. In case of statics it is only a first - very imprecise (and expensive) estimation. Users should always calculate with computer models consisting of primary structure and membrane in one holistic model.

In the following real example, we show the differences using concrete numerical values. The example shows a chambered pneumatic structure with a bending stiff ring.

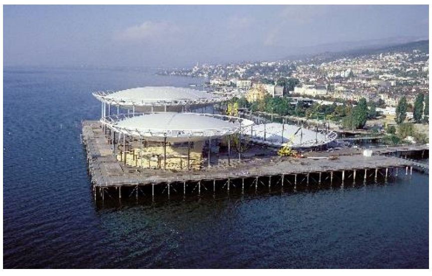


Figure 3: "Galets" for the Expo 2002, Neuchatel

Such structures are often divided into 2 subsystems. The first system is the pneumatic membrane, the second system describes the primary structure with the steel ring and the struts with cables.

Figure 4: Divided overall system. Left membrane, right steel ring with supports and cables.

The reaction forces from the membrane calculation are then applied as external loads on the primary structure in a second step. The design is then carried out using the results from the structural analysis. In the concrete example, the maximum deformation was 0.5 m and a maximum bending moment of 30000 kNm.

If the system is calculated holistically (membrane and primary structure in one system), we obtain 0.25 m for the maximum deformation. The maximum bending moment is 18000 kNm.

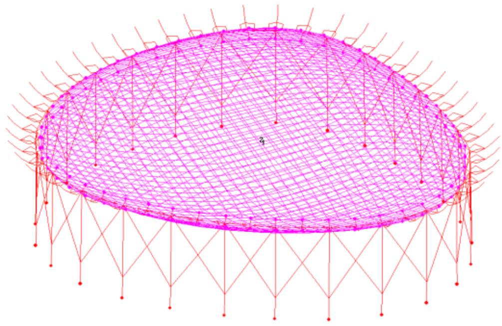


Figure 5: Membrane- and primary structure in a holistic system

The separation of nonlinear lightweight structures into subsystems is only a first, very inaccurate and expensive estimation. This fact applies to all membrane and foil structures, regardless of whether they are used as pure roof support structures or as building skins.

4.2 Form finding considering bending elements

In membrane and foil structures, prestress is of central importance; without prestress the supporting structures are not viable. The engineer specifies the desired prestress in the form-finding process and must ensure that this prestress exists also in the static load case.

If the flexibility of the bending elements is not included in the form finding process but is considered in the static load case, we do not end up with the desired prestress. In this case, all further static load cases are calculated with a wrong model.

Let us first illustrate this fact with a flat steel frame in which a membrane is clamped. The same behavior can be observed with pneumatic cushions.

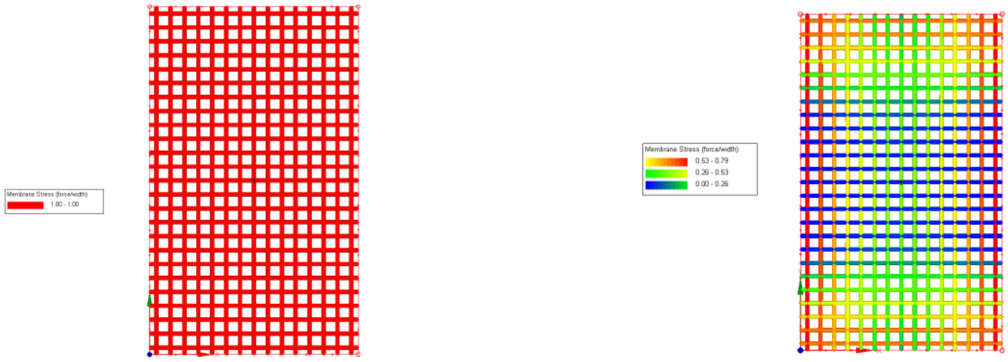


Figure 6: Form finding with fixed boundary and prestress 1:1 (left), Statics with free boundary and lower prestress (right)

It is therefore necessary to first calculate a mixed form finding. By this we mean the calculation of the force density-controlled membrane elements together with the elastically controlled bending stiff elements in one model. As a result, we obtain a deformed geometry with the desired prestress in the membrane or foil. Based on this result, new unstressed lengths for the membrane elements can be determined and transferred to the model.

In this way we obtain a static model in which the bending stiff elements and the membrane elements are elastically controlled and the desired prestress is maintained, although the bending elements deform.

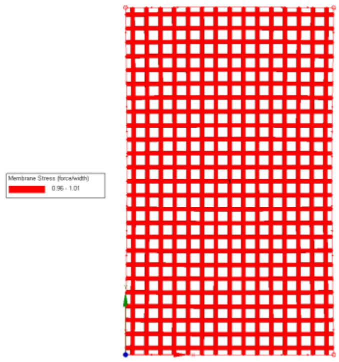


Figure 7:Statics with free boundary and prestress 1:1

The only difference between the frame (Figure 6 right and Figure 7) is that the cutting patterns of the foil are different.

In the following we show the influence of a wrong model on a frame grid. If you look at the stresses separately in x- and y-direction, you can clearly see that the stresses decrease towards the inside.

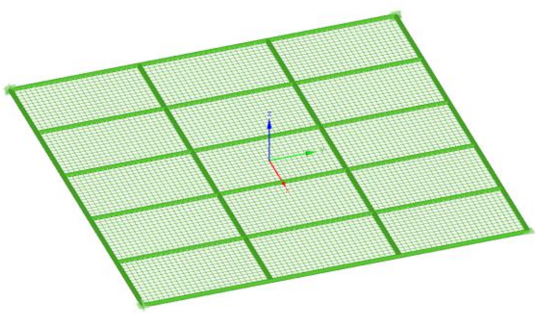


Figure 8: Frame grid 3x5, fields perspective view

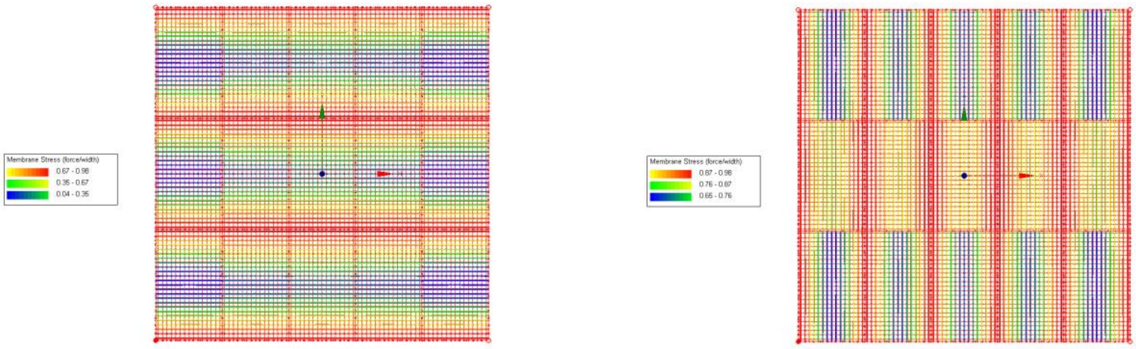


Figure 9: Wrong model and the obtained stresses in x-direction (left) and stress in y-direction (right)

The correct model gives the desired stresses of 1:1. We will refrain from using a graphic at this point.

5. Cutting pattern generation

The cutting pattern generation is an essential part of the technical process in textile architecture. It can be described as follows: Given the equilibrium shape of the curved membrane surface S, determine a set of n planar sub-surfaces $\{S_1, S_2, S_3, \ldots, S_n\}$ such that the distortion between S and S´ is minimized, where S´ is a surface of type S created by reassembling the sub-surfaces.

The task is therefore to bring a double-curved, pre-stressed surface onto a flat material of limited width in such a way that when the strips are welded and built up, exactly the shape previously modelled in the computer is created.

Cutting pattern generation is influenced by the following factors:

1.) Because double-curved surfaces cannot be mapped into the plane without distortion, efficient flattening strategies must be used.
2.) The planar strips must be as straight as possible to keep the cutting out waste as low as possible.
3.) The width of the 2D strips should be as wide as possible to minimize the amount of work. The maximum strip width depends on the roll width. Nevertheless, the distortions in the flattening process must be kept as small as possible (see 5.1).
4.) The geometrically developed surface must be corrected (compensated) to establish the prestressed surface.
5.) Corresponding seam lines must have the same length to avoid problems by joining the strips.

5.1 Surface flattening

To provide sufficient resistance against external loads membrane and foil structures have double-curvature. The double curvature gives the material sufficient stiffness to withstand the loads to which it is subjected. Therefore, the structural engineer aims to generate a form with a maximum double curvature to increase the load bearing capability efficiently. The larger the curvature in the surface, the more difficult it is to flatten the individual cutting strips to a maximum width with minimal distortion. The flattening strategy used therefore has a decisive influence on the quality of the cutting patterns.

In our software we use a method derived from map projection. The minimal distortion energy approach can be formulated as follows:

$$\Pi = \sum_{i=1}^{m} p_s((l_{o1} - l_1)^2 + (l_{o2} - l_2)^2 + (l_{o3} - l_3)^2) + p_\alpha(\alpha_0 - \alpha)^2 + p_A(A_0 - A)^2 \Rightarrow min. \qquad (5\text{-}1)$$

with:

Π = Distortion Energy $\quad p_\alpha = angle\ weight \quad p_s = distance\ weight \quad p_A = area\ weight$

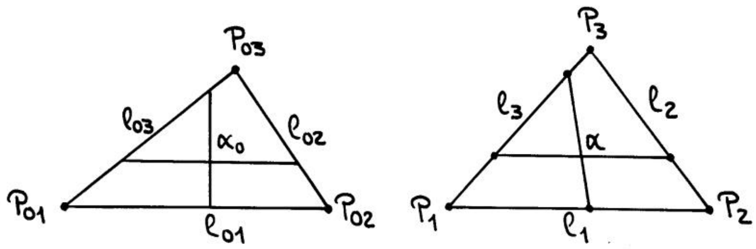


Figure 10: Non-deformed situation in 3d (left) and deformed situation in 2d (right)

5.2 Cutting patterns for pneumatic cushions

With pneumatic cushions, the connection to a supporting structure is made via a multi-part bending stiff frame profile. This means that there is no possibility for adjustment in case of inaccurate cutting patterns. Therefore, the cutting patterns must be very precise.

To avoid waste of material we must adjust the maximum patterning widths to the role widths. The maximum widths of cushion-patterns lie in the ridge line. Therefore, an automatic widths-optimization is possible using this line as guideline. For large projects, as much material as possible should be saved. The waste optimization is an economic factor for such projects. For pneumatic cushions, geodesic lines perpendicular to the ridgeline can be generated automatically and then the flattening can be performed as described above.

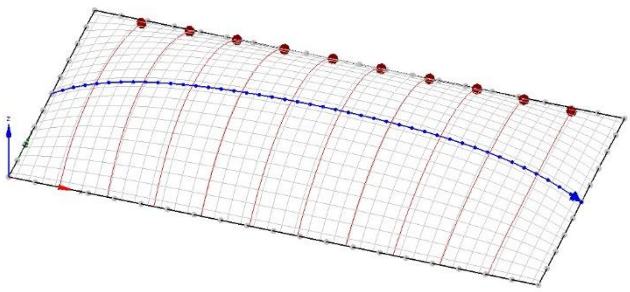


Figure 11: Ridge line as a guideline for geodesics

In the case of cushions with several layers, the position of the seam lines on the frame profiles plays an important role when generating cutting patterns. If all seam lines arrive at the same position on the frame, there will be difficulties during clamping because of the thickened material at this point. The software must provide automated methods that allow to set the seam line offsets.

6. Examples – Building skins with ETFE cushions

In the examples shown below, the techniques shown in the previous sections have been successfully applied.

The facade of the Allianz Stadium is one of the largest membrane shells in the world. It consists of 2,784 pneumatically pre-stressed cushions made of ETFE foil. Approximately half of the cushions are of different sizes and have a different shape. The cushions consist of one chamber and usually have a diamond-shaped edge.

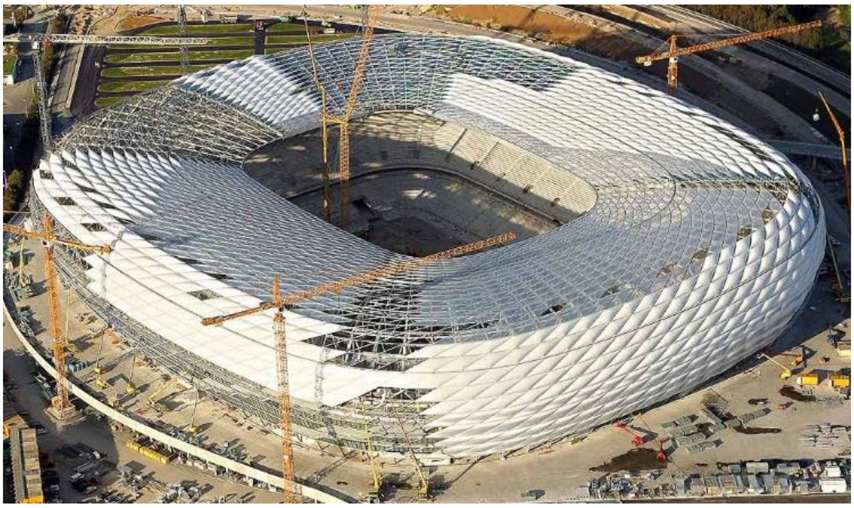


Figure 12: Allianz Arena Munich

Figure 13: Cushion mockups

Due to the large number of different cushions, it was not possible in this project to carry out the form finding and cutting pattern generation manually. To accelerate the calculation process automated methods were used. In this project the company covertex GmbH was responsible for the cushion facade, the company technet GmbH supplied the software for the automated calculation.

The parameters of the form finding for the individual cushions were specified in an Excel table, each row for one cushion. Together with the boundary geometry, the software then determined the equilibrium figures for the cushions automatically. A predefined sag was used as a break-off criterion.

Microsoft Excel - 03-12-11_Eingangsfile.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	System	Kissenknoten KN1 (global)			Kissenknoten KN2 (global)			Kissenknoten KN3 (global)			Kissenknoten KN4 (global)			ETFE		Zuschnitt, Stich
2	Kissen-Nr.	x	y	z	x	y	z	x	y	z	x	y	z	Dicke OL	Dicke UL	Stich nach Abgleich Statik IST / HdM SOLL
3	[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[my]	[my]	[m]
4	**12603**	-126406	-15634	18738	-127395	-23394	22717	-126570	-31531	22717	-125824	-23690	18738	200	200	0.738
5	**12503**	-126757	-7340	18738	-127985	-15013	22717	-127410	-23173	22717	-126421	-15412	18738	200	200	0.738
6	**12403**	-126854	960	18738	-128317	-6618	22717	-127994	-14793	22717	-126765	-7120	18738	200	200	0.738
7	**12303**	-126697	9259	18738	-128390	1783	22717	-128319	-6399	22717	-126856	1180	18738	200	200	0.738
8	**12502**	-124891	-7546	14948	-126377	-15437	18639	-125796	-23481	18639	-124555	-15484	14948	200	200	0.638
9	**12402**	-124996	633	14948	-126721	-7146	18639	-126387	-15205	18639	-124900	-7314	14948	200	200	0.638
10	**12302**	-124853	8811	14948	-126813	1152	18639	-126724	-6916	18639	-124998	864	14948	200	200	0.638
11	**12202**	-124461	16981	14948	-126650	9448	18639	-126809	1381	18639	-124848	9040	14948	200	200	0.637
12	**12401**	-122309	-984	12450	-124836	-7339	14863	-124500	-15286	14863	-122170	-8765	12450	200	200	0.510
13	**12301**	-122218	7020	12450	-124935	836	14863	-124839	-7119	14863	-122312	-765	12450	200	200	0.510
14	**12201**	-121889	15017	12450	-124785	9010	14863	-124931	1053	14863	-122215	7237	12450	200	200	0.510
15	**22101**	-121319	23001	12450	-124388	17176	14863	-124776	9225	14863	-121879	15231	12450	200	200	0.509

Figure 14: Parameters for form finding procedure

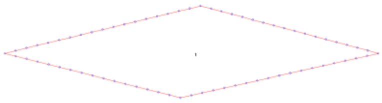
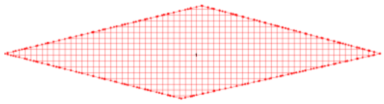
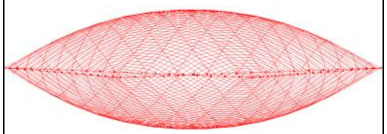
Boundary generation		Net generation		Equilibrium under inner pressure
	→		→	

Figure 15: Step-by-step process of automatic volume form finding based on the given parameters

In a second step, the cutting patterns for the top- and bottom layers were also determined automatically.

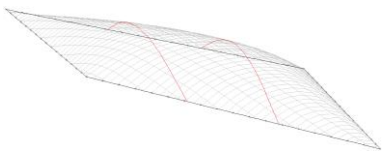
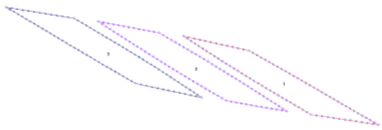
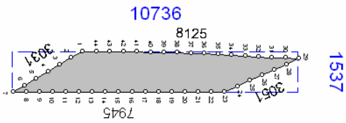
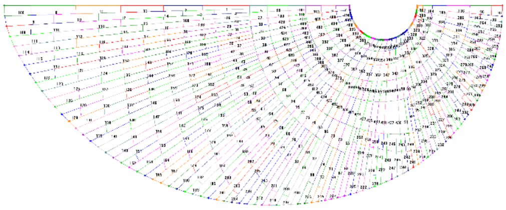
Cutting lines as geodesic lines		Cutting patterns with smallest distortions		Patterns: System line + seam-allowance as dxf file for cutting machines
	→		→	

Figure 16: Step-by-step process of automatic cutting pattern generation based on the given parameters

The second example also shows an ETFE building envelope. This is the Khan Shatyr in Astana (Kazakhstan) and is the largest tent in the world, 150 m high. The structure consists of a cable net with 836 triple-layer ETFE-cushions.

Figure 17: Khan Shatyr in Astana and cable net



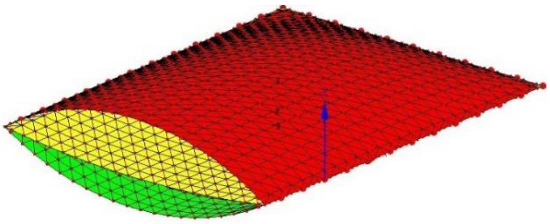


Figure 18: General plan of the cushion fields (left), 3-layer double chamber cushion (right)

In this project, too, the parameters for form finding and cutting pattern generation were read into an automated volume form finding process. The optimization process is shown in the next figure.

The process starts with desired sags (s_{d1}, s_{d2} and s_{d3}) for the 3 foil layers:

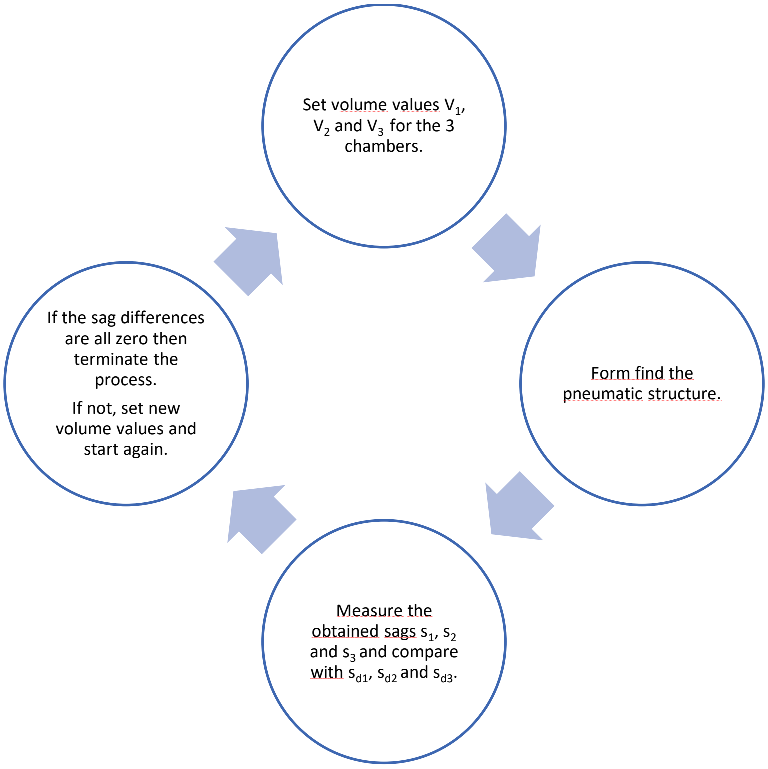


Figure 19: Form finding optimization process

The result was again width-optimized cutting patterns for the 3 layers of the 2-chamber pneumatic cushions. The cutting patterns were generated by the algorithm in such a way that the seam lines of the upper, lower and middle foil were shifted at the edges with a corresponding offset. This has prevented problems due to thickening when clamping the foil in the frame. The cushion skin was realized by vector foiltec together with bfl Tritthardt + Richter. The automated software came from technet GmbH.

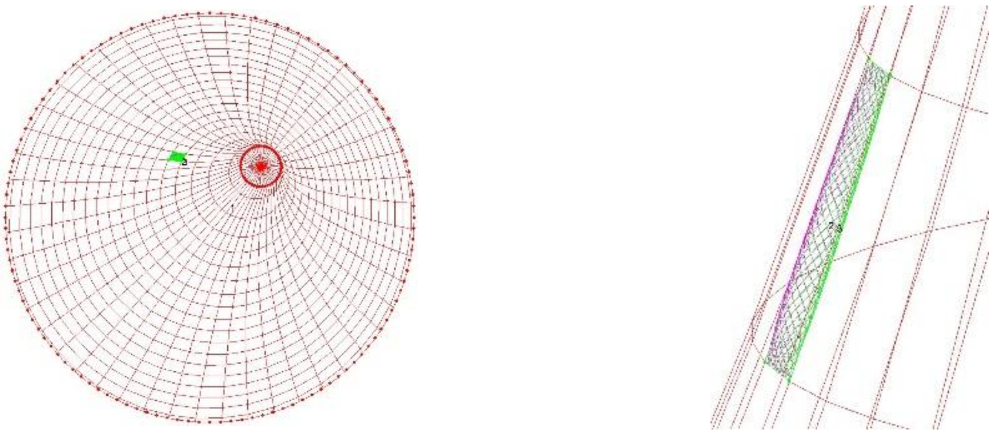


Figure 20: Top view (left) and cable net with 2 chambered cushion (right)

Especially the automatic optimization of the pattern layout is more and more important as for big ETFE-projects mass production of patterns should be managed in a short time and with highest accuracy.

7. References

[1] Ströbel, D., Holl, J. “Powerful Tools for Formfinding, Statics and Patterning of Pneumatic Structures”, Proceedings of the Tensinet Symposium, 2019, pp. 144-159

[2] Ströbel, D., Singer, P., Holl, J. „Analytical Formfinding”, International Journal of Space Structures, Volume: 31 issue: 1, page(s): 52-61, March 1, 2016

[3] Holl, J., Ströbel, D., Singer, P. “Formfinding and Statical Analysis of Cable Nets with flexible covers”, VI International Conference on Textile Composites and Inflatable Structures Structural Membranes 2013, Munich, Germany.

[4] Singer, P. (1995), „Die Berechnung von Minimalflächen, Seifenblasen, Membrane und Pneus aus geodätischer Sicht“, Dissertationsschrift, DGK Reihe C, Nr. 448, 1995.

[5] Ströbel, D. (1997), „Die Anwendung der Ausgleichungsrechnung auf elastomechanische Systeme“, Dissertationsschrift, DGK, Reihe C, Nr. 478.

[6] Ströbel, D. Singer, P, Holl, J: Holistic Calculation of (Multi)-Chambered ETFE-Cushions, Tensinet, Tensinet Istanbul, 2013