TensiNews

NEWSLETTER NR. 33
SEPTEMBER 2017
PUBLISHED TWICE A YEAR
PRICE €15 (POST INCL)
www.tensinet.com

NEWSLETTER OF THE EUROPEAN BASED NETWORK FOR THE DESIGN AND REALISATION OF TENSILE STRUCTURES

ARTICLE

ALBESILA'S TRAVELS
ARCHITECTS OF AIR

REPORT

TEXTILE ROOFS 2017

RESEARCH

KINEMATIC FORM-ACTIVE STRUCTURES

ALBESILA'S TRAVELS - Inside the Exxopolis luminarium © John Owens Photography ▲
REDESIGN FORECOURT FOR CONGRESS HOTEL - Detail view at night © Meeß-Ohlsohn ▶

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ISSN 1784-5688

Price €15
postage & packing included

n°33

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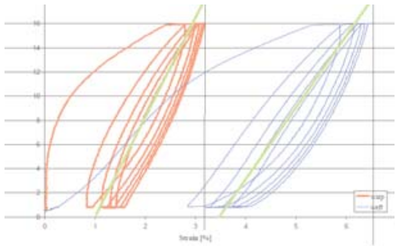
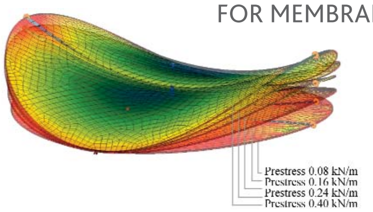
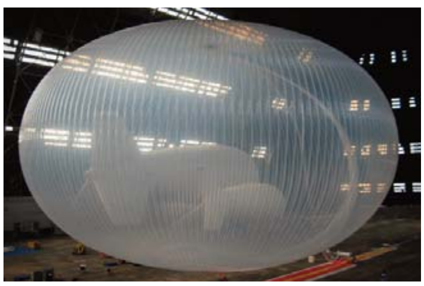
ARTICLE





RESEARCH

REPORT



Edito

Dear Reader,

I am glad to present you our new TensiNews. Recent research activities are presented in this issue, as well as actual membrane and foil projects.

The VUB Brussels is introducing the research results of Kinematic form-active structures for architectural applications, giving a summary of the workshop Lightweight Structures, that was held in the academic year 2016/2017.

One of our partners is presenting the advantages of integrated non-linear analyses for textile architecture, combining the membrane with the primary structure, so that the interaction is properly taken into account.

Two membrane roofs in Germany, with almost the same age of approximately 25 years have been refurbished recently. Both examples, the Mercedes Benz Arena in Stuttgart and the open air theatre in Tecklenburg show that all the main structural elements can be reused, and by renewing the membrane cladding, the roof structures can be up for another 20 to 25 years, with new brilliant appearance.

Other worldwide projects shown are a canopy in Germany, an ETFE tunnel in Kuala Lumpur, a pavilion in Kazakhstan and an amphitheatre in Canada. Furthermore the architects of air from the UK present work from the past 25 years.

The events this year started with Techtextil and Textile Roofs this May in Frankfurt and Berlin. Joseph Llorens was so kind to prepare a summary of Textile Roofs 2017 for us. After the summer break there will be a lot of other important conferences, like the IASS Symposium in Hamburg end of September, and Structural Membranes in Munich in October. During Structural Membranes we will have also our partner meeting and the annual general meeting.

The TensiNet partners have decided that the next TensiNet Symposium will be held in 2019 in Milan. Details and a call for abstracts will follow soon.

I hope to meet you on one of these events after the summer. Meanwhile please enjoy this issue of TensiNews.

Yours sincerely,
Bernd Stimpfle

Architect meets innovations

TensiNet Partner Sioen was represented with an inspiring tensile structure at architect@work, Kortrijk XPO (BE) held on 27 & 28 April 2017.

Please let us know when you are planning to exhibit at an architect@work event.

Extra information: http://www.architectatwork.com/

RESILIENCE & LIGHTNESS – TS2019

At the beginning of June 2019, Politecnico di Milano and its accredited laboratory on textiles and polymers TextilesHUB will host the next TensiNet Symposium, focusing on Lightness and its impact on global sustainability challenges. In an ever-changing world, innovative technologies are constantly redefining disciplines and mindsets, causing disruption and creating new hybrid concepts that are more resilient to keep up with rising sustainability demands. In this turbulent process, concept of Lightness has becoming more sound and profound, shifting its essence from vision to necessity. The conference explores these emerging scenarios of the disciplines - with the specific focus on membranes, foils and ultra-lightweight structures - and sets a new perspective for a new age of disruption that will challenge resilience and shape of both the Lightweight Architecture and the Membrane-based Construction of the future.
During the 3-days symposium: a) an exhibition will highlight the most interesting advancement of every european region associated to TensiNet; b) a field trip to the newest construction in Milan, like Regione Lombardia, City Life, Scalo Milano, Bosco Verticale will be organized.
POLIMI team: Alessandra Zanelli, Carol Monticelli, Nebojsa Jakica and Salvatore Viscuso.

Forthcoming Events

TENSILE intense program at IMS
16 – 24/09/2017 | IMS e.V.
Archineer® Institutes Dessau-Rosslau, Germany
www.tensile-intense.com

pre-symposium activities IASS
Workshops & Master classes
20-24/09/2017 | HafenCity Universität Hamburg, Germany
http://iass2017.org/frontend/converia/media/IASS17/Workshops/IASS17_booklet_ws-mc_rev5_2017-06-02.pdf

International symposium of the International Association for Shell and Spatial Structures **IASS 2017**
"INTERFACES: ARCHITECTURE . ENGINEERING . SCIENCE".
25-28/09/2017 |
HafenCity Universität Hamburg, Germany
http://iass2017.org/

12th International Conference on
Building Envelopes of the Future
02 – 03/10/2017 | Congress Center Kursaal, Bern, Switzerland
https://abs.green/program-2017

VIII International Conference on Textile Composites and Inflatable Structures
Structural Membranes 2017
Munchen, Germany |
09 – 11/10/2017
http://congress.cimne.com/membranes2017

Aachen-Dresden-Denkendorf
International Textile Conference 2017
Stuttgart, Germany | *30/11 – 01/12/2017*
www.aachen-dresden-denkendorf.de/itc

International workshop Textile Roofs 2018 *15-17/05/2018*
www.textile-roofs.de

Forthcoming Meetings

TensiNet Meetings at Structural Membranes 2017
10/10/2017 at 18.00
Annual General Meeting & Partner Meeting

Final
COST-ACTION TU 1303 NOVEL STRUCTURAL SKINS MEETING AT VUB, BRUSSELS, BELGIUM
17/10/2017
http://www.novelstructuralskins.eu/events/meetings/

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KIEFER. TEXTILE ARCHITEKTUR

REDESIGN FORECOURT

FOR CONGRESS HOTEL

Düsseldorf, Germany

The new canopy is docked to the hotel's forecourt in a floating ease and as this it provides a new eyecatcher for the Lindner Congress Hotel in Düsseldorf.

A circular steel ring with a diameter of 12m is covered with a two-layer ETFE membrane, formed as a cushion by means of the necessary air pressure. In the outer border area, a fine rope net consisting of 20 round-strand ropes lies on the upper side as well as on the lower side of the cushion. This gives the desired form to the cushion - namely as a lens - and also keeps it in shape.
In addition, the effect of a lens is intensified by the choice of the colour of the material and purposeful lighting.
For the outer border area a white, less translucent membrane is used.

3M GERMANY

TUNNEL IN THE AIR MADE OF ETFE FILM CUSHIONS

LIGHTWEIGHT SOLUTION AS NOISE BARRIER AND PRIVACY SHIELD FOR RESIDENTS

Kuala Lumpur, Malaysia

Every few minutes the driverless Kelana Jaya Light Rail Train (LRT) on an elevated railway squeezes its way through the sea of houses in the conurbation of Kuala Lumpur, the capital city of Malaysia. At the narrowest point the track runs less than three metres away from a residential building and a hotel. To protect the residents from the high noise stress, Malaysia's first "tunnel in the air" has been built. It encloses a curved section of the track with 363 film cushions, which are made from the high-performance 3M Dyneon Fluoroplastic ETFE.

Introduction

Economic success in Asia has also inflated its traffic problems to new dimensions. The solution of choice is the development of local public transport. That is also the case in the Kuala Lumpur conurbation in Malaysia, whose seven million inhabitants make it one of the most densely populated regions on the peninsula. In recent years, the route network of the Kelana Jaya LRT elevated railway has been expanded to almost 50 kilometres.

The construction of the elevated railway relieves the traffic at ground level in the same way as underground railways, but is considerably less expensive to build.
At the narrowest point of the most recent development stage, the distances between the track and the nearest house and hotel are less than three metres. That leads not only to enormous noise stress for the residents. The train passengers also had a direct view into the homes and hotel rooms. Therefore, "Prasarana Rail and Infrastructure Projects", who operates the line, decided to equip the narrow point with noise protection elements and to erect a "tunnel in the air" as a privacy shield.

1a

1b

2

Figure 1a -b. The air tunnel encloses a curved section of the track with 363 film cushions, which are made from the high-performance 3M Dyneon Fluoroplastic ETFE © Architen Landrell
Figure 2. The ETFE films for the roughly 2.500m² of exterior surface feature a smooth surface so that a rain shower is sufficient to clean them. That reduces the operational costs.

In the centre of the circle, in the area of the more pronounced convexity of the lens, a completely transparent membrane is selected, which allows the visitor to look from the bottom to the top or from the top to the bottom, and have an outlook to the forecourt of the hotel.

Kathrin Kaltenbrunner
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Figure 1. Detail view at night © Meeß-Ohlsohn
Figure 2. Detail cushion © Meeß-Ohlsohn
Figure 3. General view © Meeß-Ohlsohn

Name of the project:	Main entrance roof congress hotel
Location address:	Düsseldorf, Germany
Client (investor):	Lindner Hotels AG
Function of building:	Redesign forecourt
Type of application of the membrane:	cushion
Year of construction:	2017
Architects:	Dr. Prof. Meeß-Ohlson
Structural engineers/ Detailed engineering:	Tobias Lüdeke, Manfred Schieber (K.TA)
Consulting engineer for the membrane:	Tobias Lüdeke (K.TA)
Main contractor:	Koch Membranen
Contractor for the membrane:	Koch Membranen
Supplier of the membrane material:	Nowofol
Manufacture and installation:	Koch Membranen/ Wilfling Montagebau
Material:	ETFE Nowofol
Covered surface (roofed area):	ca. 115m²

Complex shaping with 363 individual film cushions

Architen Landrell of Chepstow in the UK, one of the leading companies for the use of membranes and films in architecture, was responsible for the implementation. The company has already installed more than 6.000 lightweight constructions in 48 countries. The challenge in Malaysia was the curved route of the track and the tight space be-tween the buildings. The company constructed the air tunnel from 363 steel frames, each one holding a pneumatically inflated cushion made of ETFE film. The frames Architen supplied where aluminium, which fixed to the primary steel tunnel structure. This primary steelwork was supplied by Victor Buyck Steel Construction Sdn Bhd. The cushions are a mixture of clear and printed ETFE film with a heavy silver frit to produce a pattern across the cladding. The tunnel has a complex three-dimensional form. None of the 363 film cushions are identical. The company developed special software to master this complexity (individual analysis and patterning). The tunnel, which is formed by a lattice of complex steelwork, supports acoustic panels alongside the track in order to give a level of absorption and the ETFE cushion give partial visual obscurity from the railway line to the hotel/apartment. In addition, the tunnel provides a stunning architectural feature which can be viewed from the ground and runs alongside one of the major trunk road into the city.

The films for the roughly 2.500m² of cushion surface were extruded by Nowofol Kunststoffprodukte GmbH & Co. KG from the high-performance material 3M Dyneon ETFE. The company produces the NOWOFLON® ET 6235Z films in thicknesses between 80 and 400 microns, both transparent and in virtually all RAL colours, as well as in an infrared-absorbing version. Transparent and silver-coloured films were installed in the air tunnel. Moreover, several empty frames allow for pressure compen-sation when trains pass through.

High fire safety and largely self-cleaning

3M Dyneon ETFE is virtually universally resistant to chemicals, including aggressive exhaust gas emissions, and is regarded as non-flammable. The high-performance material conforms to the necessary European and US standards for installation in sports stadia. Architen Landrell produced further proofs of fire safety for the Malaysian authorities – an important property in the direct vicinity of residential buildings.

Lightweight

The construction of the tunnel took place in summer 2016 without interruption of the railway operations. The individual frames were connected to the existing elevated track construction. That was only possible with a very lightweight structure. The films weigh less than five percent in comparison to a glass construc-tion. Thus, the support structure can be made lighter and more slender and cost can be saved due to less use of materials.

Maintenance

ETFE film cushions have been proving themselves for over thirty years in every climate zone in the world. Their surface is so smooth that a rain shower is sufficient to clean them for the most part. That reduces the operational costs. For the film extrusion from 3M Dyneon ETFE Nowofol Kunststoff-produkte does not need any plasticizer or additives that could migrate and result in cracks or embrittlement nor does it provide breeding ground for algae and mould even after decades of use in hot and humid climate zones.

Our client and the principal contractor on site was Victor Buyk Steel Construction Sdn Bhd.

Helmut Frisch
hfrisch@3M.com
www.dyneon.eu

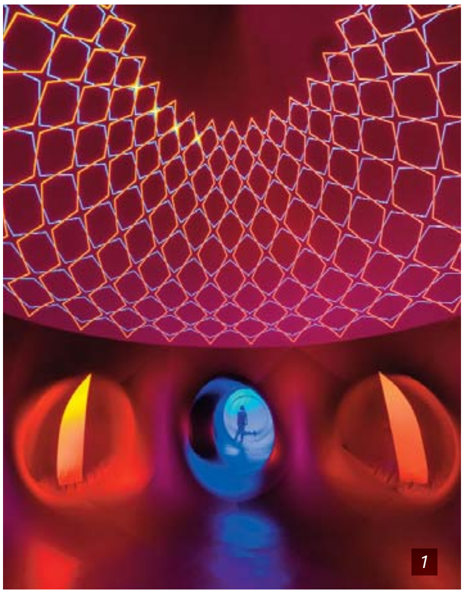
Name of the project:	Air tunnel Kelana Jaya LRT elevated railway
Location address:	Kuala Lumpur conurbation, Malaysia
Client (investor):	Prasarana Rail and Infrastructure Projects
Function of building:	noise barrier and privacy shield
Year of construction:	2016
Design:	Architen Landrell
Contractor:	Victor Buyk Steel Construction Sdn Bhd
Supplier of the membrane material:	Nowofol Kunststoffprodukte GmbH & Co. KG
Manufacture and installation:	Architen Landrell
Material:	NOWOFLON® ET 6235Z
Covered surface:	2.500m²

ARTICLE

ALBESILA'S TRAVELS

UK & WORLDWIDE ARCHITECTS OF AIR

25 YEARS OF BUILDING WITH AIR AND LIGHT



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Introduction

Architects of Air build ***luminaria***: monumental pneumatic membrane structures designed to generate a sense of wonder at the phenomenon of light and colour. British designer Alan Parkinson founded Architects of Air 25 years ago and has since created a new luminarium every year. His latest luminarium bears the name *Albesila* and was first revealed in Architects of Air's hometown of Nottingham in May of this year.

Albesila has since gone on to travel the world. In their 25 years of existence the luminaria of Architects of Air have visited over 40 countries, receiving more than three million visitors. Their accessibility to the broadest public was perhaps most exemplified in Sao Paulo where bankers and street kids happily explored the luminarium side by side.

The communal and inclusive vision of the company derives from the kaleidoscopic beauty of the inside of its luminaria (Fig. 1). The surreal experience of entering a luminarium has a magic about it that crosses culture and age. As one visitor described it, being inside felt like "being somewhere between a womb and a cathedral". This article will introduce you to the history of Architects of Air's magnificent membrane structures, and to their latest creation.

Beginnings

Experiments with large inflatable spaces have been undertaken since the 1940s, but really took off in the 1960s and 70s. NASA researched the potential for deploying a pneumatic *lunar worm* as early as 1966[1] and the British government published Cedric Price's research report *Air Structures, A Survey* in 1971[2]. One could say there was an air of futuristic optimism around pneumatic membrane structures at that time. The potential of pneumatic environments had not gone by unnoticed by architects like Dante Bini and artists like Graham Stevens. Bini searched for ways to use air as the formwork for concrete domes[3]. Stevens researched the application of a 400m long pneumatic, floating causeway to connect ships and land[4].

Alan Parkinson's work with inflatables started as part of a project working with Nottinghamshire Probation and After-Care Service in Nottingham (UK) in the early 80s. There a simple airbed structure had been created to provide a play/therapeutic function for community groups identified as 'disadvantaged'. In repairing this airbed structure (Fig. 2) Alan's interest in inflatable structures grew and he began experimenting with different forms creating an ensemble of different structures to load into the back of the project's van. These structures were used for recreational schemes with a special focus on special schools and centres for adults with learning difficulties.

By the mid-80s Parkinson had designed and built his first pneumatic structure that, in retrospect, can be counted among the family of luminaria. Unlike the airbed, the *Environment 1* structure was designed to be entered. Visitors would take off their shoes, walk through an airlock, and enter a maze of tunnels filled with vibrant light that filtered through the different areas of coloured PVC (Fig. 3).

It was during this time that it became clear to Parkinson how strongly ingrained the public perception of inflatable structures was as being places for throwing oneself around. If his structures were going to be appreciated for their visual qualities then he would have to frame them differently. There began a number of collaborations with dance and theatre companies who devised interactive performances designed to bring the aesthetic qualities of the structures to the foreground of visitors' perception. One such collaboration led to the creation of *Eggopolis* in 1990. This structure was the touring theatre of the *Touchbag Project* where professional actors and amateur actors from a centre for adults with special needs performed to audiences in different locations around the UK.

Design and construction

The community project came to an end and in 1992 Parkinson founded Architects of Air to tour his *Eggopolis* structure (Fig. 4). *Eggopolis* consisted of a geometrical grid of dark tunnels that connected eight colourful egg-shaped domes. It was the first structure to

2

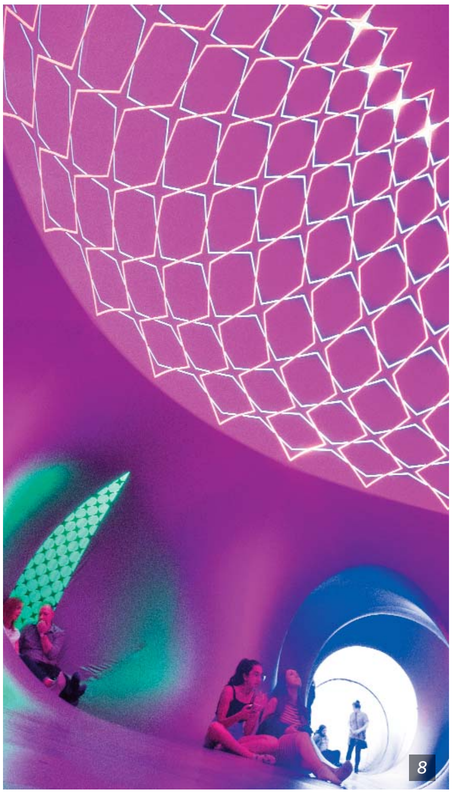
3

incorporate many of the typical design-elements that can be found in later structures. Apart from the large focal points (the domes) and the tunnels that connect them, there were 'pods', columns and colourful motifs.

Creating a new luminarium is a process that takes roughly one year. Design work generally begins during late summer with Parkinson drawing from ideas, notes and sketches that he has collected in his A4 squared notebook. In the tranquil setting of his home-office near Geneva, with a window view of lush green rolling hills beyond his sloping garden, he will start by working on a labyrinthine plan for his new luminarium (Fig. 5). A strong sense for the behaviour of pneumatic spaces and a deep feel for envisioning the interior three-dimensionality and play of light inside the structure is a quality that he has developed over his 25 years of building luminaria. Nowadays, a dialogue with Architects of Air's workshop staff in Nottingham starts at an early phase of the design process. Backed by CAD software and the possibility of building life-size prototypes, extensive email dialogues and frequent Skype calls between Parkinson and the workshop have become routine. The luminaria of Architects of Air are inspired by nature, by the works of Frei Otto and Buckminster Fuller, Islamic architecture and the geometrical principles of Archimedean solids like the truncated icosidodecahedron. With his latest structure *Albesila* Parkinson and his Nottingham-based team decided to revisit some of the design aspects of Architects of Air's first structure *Eggopolis*.

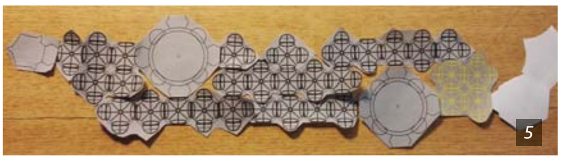
Albesila

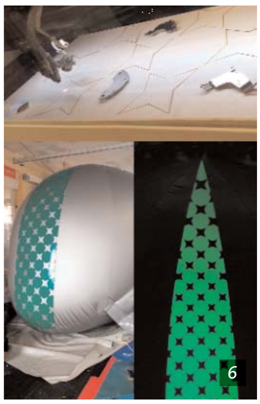
For *Albesila*, the design sketches and CAD models materialized into the first actual physical elements of the new structure in December of 2016. These first builds of 'pods' and small domes are always an exciting moment for the entire Architects of Air team. It marks a go/ no-go point: After inflation and inspection of the first few full-scale elements it was decided to go ahead with the build of the entire 1000m^2 structure (Fig. 6). As with every luminarium, this requires a large up-front investment by Architects of Air. Material and structure-specific equipment has to be acquired and experienced freelance build staff is contracted. From an acquisition point of view the challenging task starts of finding presenters, often festivals or cultural centres, who are willing to programme the new luminarium as part of their event. Most of these events take place between May and September. So starting a new build in December leaves not much room for error or delay. Building a luminarium has been compared to dressmaking: a true sense for the final three-dimensional result only becomes apparent when the dress is worn. The same goes for a luminarium. After about three months of hard indoor work by the workshop team *Albesila* was brought to a gymnasium for its first full test inflation (Fig. 7).



When the overall design has reached a stage where the first elements of the new luminarium can be built, the workshop-team will develop flat, two-dimensional cutting templates. These templates have many curves and complex corners. Unlike permanent pneumatic structures (like ETFE coverings or facades) the individual pieces that make up a luminarium are not heat or ultrasonically welded. Therefore, even after 25 years and many experiments, hand cutting and gluing each single piece of PVC is still the favoured manufacturing technique. There is a staggering 10.000m of seams in *Albesila*. These seams are a vital aesthetic aspect of each luminarium. Where these connect translucent elements of material, their width is controlled to 12mm to simulate the lead in a stained glass window. There is an elegant balance of logic and beauty about the elements that make the skin of a luminarium: the PVC patterns must not be too large and must make sense structurally, but they should also emphasise the sculptural beauty and identity of the luminarium (Fig. 8).

Figure 1. The colourful inside of the main dome of the new Albesila luminarium. All colours are produced by natural light filtering through the membrane. © John Owens Photography
Figure 2. Alan Parkinson built pneumatic structures, like this airbed structure, as part of a community project in Nottingham during the early 80's. © Alan Parkinson
Figure 3. The Environment 1 structure was created in 1985 and was Parkinson's first structure to be entered. © Alan Parkinson
Figure 4. Eggopolis was the Luminarium that marked the beginning of Architects of Air in 1992. © Alan Parkinson
Figure 5. Exploring different configurations for the new Albesila luminarium. © Alan Parkinson
Figure 6. Templates for some of the first elements of Albesila were laser cut. These were then used in the making of green 'windows' of several of the structure's 'pods'. © Alan Parkinson
Figure 7. The first full test inflation of the nearly completed Albesila luminarium on March 28. © Eric Schrijver
Figure 8. The coloured, translucent seams on the topside of the main dome of Albesila. Depending on the time of day, the interior colour changes spectacularly. © Alan Parkinson





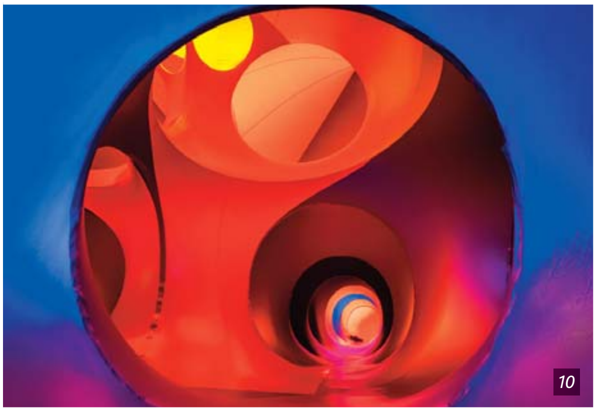


Figure 9. Albesila at its premiere event in Nottingham, UK in May. © Alan Parkinson

Figure 10. Blue, red and yellow blend beautifully around one of the central elements inside the Albesila luminarium: a geometrical complex column or tree. © John Owens Photography

Figure 11. The Katina luminarium (including the experimental Monochrome Dome in the top right) was built in 2016, here illuminated from the inside at an event in Heerlen, The Netherlands. © Luc Lodder Photography)

Figure 12. Visitors wandering through Albesila's large labyrinthic interior. © Alan Parkinson

Figure 13. Build-workshop participants working on a segment of a larger structure. © Alan Parkinson

Travels

The way a luminarium is designed as being modular, packable and ephemeral perhaps makes it the ultimate lightweight membrane structure. When *Albesila* was finished it was disassembled into manageable sections that were then rolled, folded and packed separately. The whole structure, including a large flight case with tools and documents, nine large air blowers, three small air blowers, a sound system, electric cables and distributers, pins and hammers, foam matting, signage, repair kits, spare PVC, hundreds of straps and a dozen or so rolls of tape are all packed neatly in six EPAL-size cages. These cages can then be shipped to events anywhere around the world.

Like most luminaria, the première event for *Albesila* was in Architects of Air's hometown of Nottingham in May 2017 (Fig. 9). At any exhibition Architects of Air provide a team of Exhibition Managers to accompany the luminarium. They assure the proper installation of the structure and its safe operation for the duration of the exhibition. The Exhibition Managers work with a local production crew to get the luminarium unpacked, assembled and inflated. They then train a local team of about 10 stewards to manage the luminarium when it is open to the public.

Generally, Architects of Air has four or five different luminaria touring simultaneously; each accompanied by its small crew of Exhibition Managers in constant contact with both Alan Parkinson (as Artistic Director) and Mado Ehrenborg (as Managing Director), as well as with workshop management for any production or logistic support.
But the Exhibition Managers are at the final end of on-site production decision-making. They often face interesting site-specific challenges varying from lampposts and other objects that "weren't supposed to be there", to changing weather conditions.

Sometimes there can be issues with the material. The isotropic properties of the specially produced PVC make it an ideal material for the complex double curved surfaces that are formed when a luminarium is inflated. However, variations in the chemical composition of the PVC can cause problems. It has happened repeatedly that different batches of PVC seemed to react differently to environmental factors like heat, cold, UV-radiation and atmospheric pollution. Working closely with PVC-film manufacturers has proven to be an absolute necessity to ensure the right material properties in terms of translucency, reflectance, strength and overall durability. Still, Exhibition Managers are well trained and equipped for on-site repairs when necessary.

The luminaria are rather delicate, so small cuts or pinholes are inevitable.

Many visitors who enter a luminarium for the first time find it hard to believe that all those astounding colours, hues and shades are a result of natural light filtering through the coloured, translucent PVC and their blending on the curved, sloping, silver-opaque surfaces (Fig. 10). At some events, lights are set up outside and around the luminarium so opening hours can be extended after sunset. In other cases, luminaria were closed for visitors during the evening, but left inflated with bright lights set up on the inside. This creates a rather magical display of the luminarium where it becomes radiant like a collection of vast Chinese lanterns (Fig. 11).

Bright future

Even though the new *Albesila* luminarium with its 24 egg-shaped domes pays homage to the early *Eggopolis* luminarium, it also breaks with Architects of Air's design tradition. The idea of the labyrinthine layout and visitor's journey has been approached differently with the introduction of a more symmetrical layout. *Albesila* is also much brighter on the inside than many of its predecessors, revealing an ocean of liquid colour once one steps through the airlock. (Fig. 12).

Like all previous luminaria *Albesila* is a large structure but scale is not an end in itself but simply a by-product of the need to create enough of a journey for visitors to lose themselves, which in turn heightens their senses. Apart from his large luminaria, Parkinson would like to work towards establishing more small-scale work, not aimed at the regular large crowds per se but for special places and intimate audiences. One such structure, the *Little Dome Project*, was created as something financially and technically accessible for collaborative community/ social activities. This approach taps deep into the soul of Architects of Air where accessibility and inclusiveness are a fundamental drive. It is this philosophy that has brought Architects of Air to develop a series of build-workshops: open to a wide range of audiences varying from corporate to academic and from festivals to schools. These workshops do not (yet) incorporate membrane-specific design techniques like form finding, FEM-analysis and algorithmic design. They do however allow Architects of Air to share their experience in creating elegant pneumatic membrane structures in a way that is hands-on and inspiring[5]. Participants quickly get a feel for design, patterning and basic pneumatic principles by creating large-scale objects in a matter of hours (Fig. 13).

When *Albesila* premiered in Nottingham, Parkinson described stepping inside as "[…] being suspended on a threshold between matter and light where surface has lost its materiality and light has gained tangibility, like a gateway to another reality. And once the last visitor has departed on the final day of this exhibition *Albesila* will be demounted and packed and may be on its way to the next exhibition within a couple of hours. Such is the beauty of ephemeral, monumental membrane architecture."

25 years of building with air and light: if you want to experience being inside a luminarium yourself, or if you would like more information after reading this article, check out Architects of Air's website!

Eric Schrijver
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Project name:	Albesila
Project type:	Luminarium (art sculpture)
Location address:	Traveling (see Architects of Air website for locations)
Client (investor):	Architects of Air/ Luminarium Co. Ltd.
Function of construction:	Art sculpture / installation
Year of construction:	2017
Architect/ designer:	Alan Parkinson/ Architects of Air
Structural engineer:	ART Engineering GmbH
Membrane material:	PVC
Manufacturer of membrane:	Alkor Draka, Riflex, Sauleda
Total area of membrane:	4500m²
Covered surface (wrapped area):	Occupies a space of around ca. 1.000m², with voids a net area of ca. 750m²

References
[1] Feasibility Study for Lunar Worm; NASA Contractor Report CR-66098; F.A. Dobson, D.G. Fulton; 1966.
[2] Air Structures: A Survey; UK Ministry of Public Building and Works; C. Price, F. Newby, R.H. Suan; 1971.
[3] Dante Bini (b. 1932) is still active. His company Binishells is based in Beverly Hills, CA, USA.
[4] Among Graham Stevens' most notable pneumatic projects are Hovertube (1970) and Desert Cloud (1974).
[5] More information is found in their book: The Most Beautiful - 20 Years of Architects of Air; Architects of Air; A. Parkinson, A. Mitchelson; 2013.

ARTURA

LOOK! LOOK! LOOK!

Entering the magical space of the walled garden at Berrington Hall, a Palladian mansion in Herefordshire, visitors encounter a translucent pink pavilion sculpted to resemble a pineapple. Entitled 'Look! Look! Look!', this temporary structure is constructed from plywood and steel and covered with a tensile membrane made from M-screen 8503 by Mermet. The artists, Studio Morison, worked with structural engineers Artura Design and Engineering Ltd to realise their design. Beginning with an 'origami' model, replicating the crisp sharpness of the original model's paper folds on a large scale was achieved by computer modelling and CNC cutting a plywood framework and clamping the membrane around the edge of each of the 80 individual frames before bolting them together. Reinforcement and stabilization of the structure was achieved by the inclusion of steel flitch plates and tie rods into the timber framework transferring loads down to its screw piled steel base.

Look! Look! Look! has been commissioned by the National Trust to celebrate the restoration of Berrington's Capability Brown gardens. Drawing upon the site's Georgian spirit, Studio Morison has created a structure inspired by the temporary garden gazebos, marquees and follies of the era - spaces of delight in which to converse; listen to music; take tea; indulge in amorous liaisons. Most strikingly the imagery of the pineapple hints at wealth, prestige and decadence, an 18th century status symbol that was grown at Berrington.

Josiah Wedgwood, pivotal figure of the Midlands Enlightenment, and master of the fusion of technology and beauty, famously produced teapots in the form of a pineapple. Doubtless he would've approved.

Look! Look! Look! Can be visited by members of the public until December 2019.

Artura
info@artura.ltd
www.artura.ltd

Membrane structures are often used as an interim measure and therefore rarely survive longer than 20 years or so. Textile structures in particular stand out in this context due to their special aesthetics and their demolition often means that some true engineering works of art are lost. One exception is the roof of the open-air theatre in Tecklenburg – it is a fine example of just how durable lightweight constructions can be and the potential inherent in such structures. 25 years ago, Freilichtbühne Tecklenburg e.V. wanted a rain canopy for its annual summer festival. A retractable roof was developed by consulting engineers IPL, from which the formTL engineering office emerged in 2004.

1c

LONG LIVE THE MEMBRANE

Tecklenburg, Germany

THANKS TO THE ENGINEERING OF FORMTL THE OPEN-AIR THEATRE HAS BEEN EFFICIENTLY AND SWIFTLY REFURBISHED.

In poor weather the roof can be extended to shelter the audience while in dry weather it allows a clear view of the sky. The structure consists of six filigree cable girders from which five longitudinal rails are suspended. Six steel arches with a carriage to which the double-layered membranes are attached move along these rails. As soon as the roof is extended, the membranes are inflated into cushions, so making them wind-resistant, covering an area of 29x40m. When retracted, the membranes become parked in a type of garage which protects them from bad weather. This unique structure – there are only a few comparable structures of this kind – continued to win over the clients even after over 20 years of operation with its timeless design and high functionality. The society therefore decided to maintain and renovate the cushion canopy.

1a

1b

Client	Freilichtbühne Tecklenburg e.V.
Design	IPL, Radolfzell/DE
Refurbishment	formTL ingenieure für tragwerk und leichtbau gmbh, Radolfzell/DE
Construction and manufacture	CENO Membrane Technology GmbH, Greven/DE

Figure 1a. The retractable roof before refurbishment © Freilichtbühne Tecklenburg
Figure 1b&c. The retractable roof after renovation © R. Borgmann
Figure 2. Cutting pattern layout of a membrane cushion
Figure 3a,b&c. Details © R. Borgmann

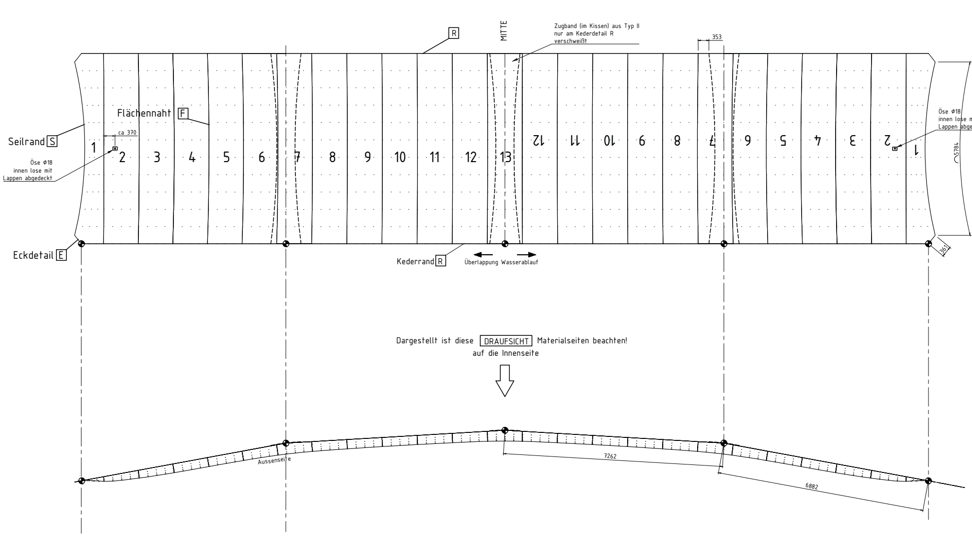
Membranes age at different rates: fixed structures usually have a service life of between 15 and 30 years. In the case of mobile structures, a service life of around 10 to 15 years may be expected as movement wears out the coating and fibres, so reducing the strength of the fabric more rapidly.

An inspection carried out in 2010 revealed that only the membranes needed to be replaced. Together with CENO Membrane Technology, who had already constructed the canopy in 1993 under the company name of Carl Nolte, formTL developed the refurbishment. One big advantage was that the project had already been designed 25 years before in 3D and all the documents, from the drawings to the analysis, to written correspondence, were kept in formTL's digital archive. This meant that all that was necessary was to carry out a comparison of the measurements of the disassembled membranes and fittings with the old plans. As there only a few discrepancies were found, formTL produced the cutting pattern which were adapted to the new membrane material within a month (Fig. 2).

An optimized material was used for the highly stressed cushions which withstands more than 100.000 folds. The correspondingly manufactured membranes were transported to the site and were easily and quickly installed. During the course of the refurbishment, not only the service life of the structure was extended but also the process of opening and closing the roof was accelerated with more powerful suction and pressure blowers.

The Tecklenburg open-air theatre is a remarkable example that is well worth the maintenance and refurbishment of membrane structures, also from the point of view of design and cost efficiency. Tecklenburg can certainly rest assured that it now has 20 years of dry summer festivals to look forward to!

formTL ingenieure für tragwerk und leichtbau gmbh
info@form-TL.de
www.form-TL.de



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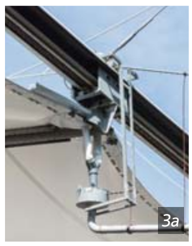


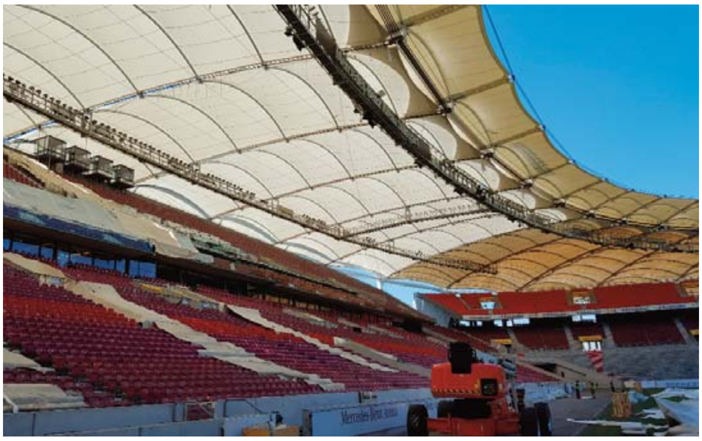
3a

3b

3c

REPLACE ROOF OF MERCEDES-BENZ ARENA

Stuttgart, Germany



VfB (Verein für Bewegungsspiele) Stuttgart's home stadium roof which is over 24 years old was replaced with material from Low & Bonar. The performance materials provider supplied the architecture membrane to the Mercedes-Benz Arena's roof. Not only was the timing of the replacement work challenging as it needed to be completed before the August return of VfB Stuttgart for the start of the First Bundesliga, but specialist skills were required as the membrane hovers 18 to 35m above the ground.

Made of a special dense woven fabric that is coated with a fluoridated nano-topcoat which makes it easier to clean - improving performance - the MEHGIES® Valmex® Mehatop® membrane can be pre-produced, shipped to the site and erected directly saving valuable time. These factors played a role in its selection by German design consultant Schlaich Bergermann Partner and the project managed from asp Architekten Gmbh.

When the stadium was rebuilt as a mere football arena in 2011 and the pitch was lowered, the contractor decided to keep the membrane roof from 1993 and prolong it towards the inside in order to cover the additional rows next to the pitch. During these works a crane fell into one of the older membrane fields and after long years of discussing the one or the other options it was finally decided in 2016 that a complete new roof would be the best solution for this dinosaur of textile stadia roofs.

The company Pfeifer Seil und Hebetechnik GmbH that is well experienced in contracting stadia roof all over the world won the bid for the Stuttgart renewal. Together with world renowned engineering and design consultants Schlaich Bergermann Partner and the architects asp they chose Low & Bonar's Valmex membrane as the perfect match for the task ahead. Apart from the deliver conditions that suited the tight project plan it was mostly the coating's recipe which was crucial in this choice. The membrane contains the right amount of TiO_2 which was essential according to the elaborate specification. Additionally Low & Bonar's material has a Nano coating that lowers down the material's surface energy and hence serves an easy cleanability. This effect is better known as the lotus effect: droplets of water only build-up a minimal contact surface with the material and rinse off easily and most of all quickly – taking away dirt particles on their way down.

Brett Simpson, CEO commented: "We pride ourselves on the quality of our performance materials. Valmex fabrics have been proven to last for decades due to particular properties of the material. This saves on long-term maintenance and replacement costs and adds to the venue sustainability."

Low & Bonar has previously equipped the Poznan stadium in Poland for the 2012 European Championships (See TensiNews 20 page 10-11) and

Konya football stadium in Turkey along with numerous stadia around the world.

Together with two other current stadia projects Mercedes Benz Arena belongs to Low & Bonar's "Hat Trick" of this year's autumn. The respective three stadia are in three different parts of the world: the one in Stuttgart, Germany, the stadium in Volgograd for the upcoming FIFA world cup in Russia and a cricket stadium in Lucknow, India – all completed within the second half of 2017.

Katja Bernert
Katja.Bernert@lowandbonar.com
www.lowandbonar.com
© *Paolo Giugliano*

Name of the project:	Replacement of the roof cover of Mercedes-Benz arena
Location address:	Stuttgart, Germany
Client (investor):	Stadion Neckarpark GmbH&Co.KG
Function of building:	sport facilities, stadium
Project Manager:	asp Architekten Gmbh
Year of construction:	2017
Conceptual design & construction design:	Schlaich Bergermann Partner
Contractor:	Pfeifer Seil- und Hebetechnik GMBH
Supplier of the membrane material:	Low & Bonar
Manufacture and installation:	Pfeifer Covertex, Shanghai and Pfeifer Seil- und Hebetechnik GMBH
Material:	MEHGIES® Valmex® Mehatop®
Replaced surface:	approx. 37.000m²

TEXTILE ROOFS 2017

THE TWENTY-SECOND INTERNATIONAL WORKSHOP, BERLIN

Textile Roofs 2017, the twenty-second International Workshop on the Design and Practical Realisation of Architectural Membranes, took place on 15–17 May, 2017 at the Archenhold Observatory Berlin, and was chaired by Prof. Dr.-Ing. Rosemarie Wagner (Karlsruhe Institute of Technology, KIT) and Dr.-Ing. Bernd Stary (Berlin Academy of Architectural Membrane Structures, AcaMem). It was attended by 83 participants from 13 countries covering two continents. Once again, the attendance demonstrated the success of the event, which has become firmly established since it was first held in 1995.

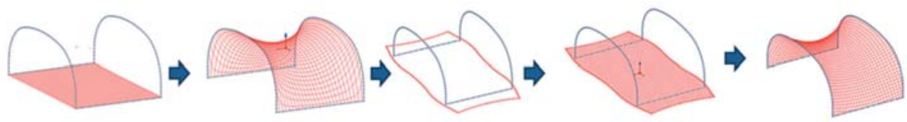


Figure 1. Boundary mapping in the form finding procedure leads to optimal stressed membrane structures, a useful capability for equidistant cable meshes.

Computational modelling of lightweight structures

Dieter Ströbel, technet GmbH.
http://technet-gmbh.de/index.php?id=74&L=1

A complete overview of the software product "Easy" by "technet GmbH" was presented by Dieter Ströbel, including the company profile and the features of the system for the analytical form finding, statical analysis and cutting pattern generation of membranes together with their fundamentals. He also highlighted different possibilities such as the boundary mapping in the form finding procedure (Fig. 1) and the capability of analyzing different behaviours under loads with different material directions of warp and weft. Regarding applications, he highlighted the optimization of textile halls with precise 3D models, considering the interaction between the steel or aluminium frame and the membrane.

In summary, D.Ströbel formulated that computer models collect information from many experts and have to be correct, precise, complete, generated in a fast way and used for mass production if necessary. He finally announced the "PreDesigner" free software for modelling.

The lightweight design approach

Jürgen Hennicke, IL - University of Stuttgart & Danube University, Krems.

Jürgen Hennicke began his lecture emphasizing that lightweight structures are not new. Slides included the Bedouin tent, the retractable roof of the Pompeii amphitheatre, radiolarian, spider webs, grid shells and bubbles. They satisfy the same physical and natural laws as our contemporary designs, that are much more rough and primitive. He provided different examples

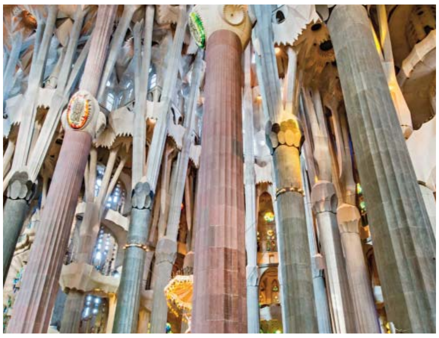


Figure 2. Trees collecting forces and bringing them down at the Sagrada Familia basilica, Barcelona 2008.

of simple structural concepts such as the Stonehenge standing stones and lintels (3.000 ~ 2.000 BC), the trussed constructions that minimize the flexural-resistant structures and the tree-shaped supports that collect forces and bring them down (Fig. 2).

The possibilities of grid shells and inflated tubes were also illustrated, mentioning particularly the Mannheim Multipurpose Hall and Restaurant at the Federal Garden Exhibition 1975 designed by C.Mutschler with F.Otto and O.Arup, in danger of extinction. Believe it or not, the city council of Mannheim decided in June 2016 by a large majority the demolition of the multihall if it should not be possible to collect a significant amount by end of 2017.

The conclusion referred to lightweight and membrane structures as everyday architecture which can satisfy all our needs as living beings in a built environment, increasing our physical, mental and social quality of life in harmony with the natural environment as a reconciliation between man and nature and with himself.

Figure 3. Ingenhoven & Partner, Architects, 2002: Kapuzinercarrée, Aachen. The Texlon® ETFE system accommodates a much larger range of structural movement than conventional cladding systems so that the overall structural weight is reduced by decreasing the stiffness.

Ageing behaviour of ETFE foils

Carl Maywald, Vector Foiltec.
http://www.vector-foiltec.com/

Stability of ETFE was the main topic and conclusion of Carl Maywald's lecture. First application was the 1982 Burger's Zoo in Arnhem enlarged by the Mangrove Hall 35 years later. He mentioned a series of applications, including the Desert Hall (Burger's Zoo, Arnheim 1982), where the size of the cushions was limited because of road transportation limitations, the Chelsea Hospital (London 1990), where ETFE was adopted because it was cheaper than glass, and the Aachen Kapuzinergraben 2002, where the historic façade was protected without need of columns, saving steel compared to the glazed solution (Fig. 3).

He listed ETFE main characteristics as high transparency, UV stability, flexibility, low weight, long lifetime, self cleaning, outstanding fire performance, recyclable, high chemical resistant and provides acoustic comfort. Regarding longevity, he showed several tests that reveal extraordinary stability and no chemical degradation under environmental conditions. He finally left a couple of lapidary sentences for posterity: "Innovation comes from the industry" and "Let's turn innovation into education!"

Detaling

Josep Llorens, School of Architecture, Barcelona. http://sites.upc.es/~www-ca1/cat/recerca/tensilestruc/portada.html

J. Llorens' presentation was a kind of academic master class about detailing textile roofs and structural membranes emphasizing that detailing is a significant part of the design process. It is critical to the overall conceptualization and the resulting structure, because details are not only derived from the general idea, but end up defining the result. They are essential to the requirements of the entire structure, including behaviour, materials, geometry, installation, durability, maintenance and visual expression.
A typology of details for fabric structures in architecture was presented. It included seams, edges, corners, high and low points, ridges and valleys, cables, fittings, and anchors. Many examples were shown and discussed keeping in mind that:
a) Details cannot be directly transplanted from a repertoire, since they have to be adapted to the requirements of each case. Solutions are successful when they meet the specific requirements of every application. Changing the requirements means that the design must be changed.
b) Detailing has to be taken into account from the beginning of the design process. It is not an independent step, because it is also essential to the general requirements of the whole structure. Details are not an afterthought.
In addition, the professor presented a data base to facilitate the coordination between the fittings that converge usually in most connections, which can be visited at the above address.

Fifty years of relaxation

David Wakefield, Tensys Limited, Bath. http://www.tensys.com/

David Wakefield. another veteran rider, summarized his extensive experience in membrane engineering including form finding, load analysis, patterning, dynamic fluid flow simulation, hydrostatic loading, ponding assessment, installation, failure propagation analysis, and supervision. The fields of applications have not been limited to mechanically prestressed membranes. They also include pneumatic cells, kites, lighter than air systems and balloons illustrated by a wealth of examples (Fig. 4).

Figure 4. NASA super pressure balloon, Tensys.

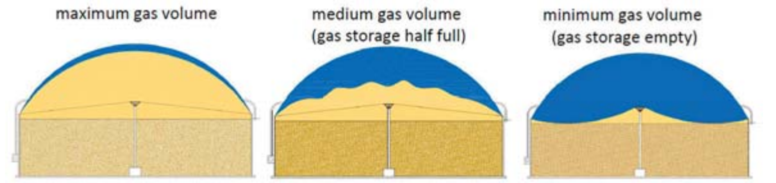


Figure 5. Seybold biogas pneumatically tensioned storage system.

Membrane biogas storage systems

Christopher Seybold, H.Seybold GmbH & Co. KG, Düren. http://www.seybold-dueren.de/

The number of biogas plants in Germany has grown from 3.711 in 2007 to 8.075 in 2016 and the installed electrical power from 1,3 to 4,1GW. The biogas is stored in cylindrical enclosures roofed by pneumatically or mechanically tensioned structures, which have opened a new field of application to the structural membranes. The pneumatically tensioned storage system consists of a double layered spherical cushion that can be flat (1.000m^2), quarter ball (2.300m^2) or hemisphere (5.800m$^{2)}$ with air pressures ranging from 2,5 to 4,5mbar (Fig. 5).
Two approaches were presented for the cutting pattern: radial or parallel. The radial cut mobilizes stress concentration in the centre. It is used for hemispheres because they have 45% to 48% height/diameter ratios. The almost parallel cut is suited for shapes up to a height of 30% of the tank diameter. It does not concentrate the stress in the middle and its production is more cost-effective.
A research programme has been launched by Seybold, KIT, technet and Wacker Ingenieure to study the interactions between external weather conditions and internal plant operating parameters for the safe and adequate calculation, dimensioning and manufacturing of biogas storage systems.

Tensile Structures: welding and structural integrity

Wojciech Staniszewski, FIAB, Sp.z o.o.Sp.k. http://www.FIABmachines.com

Professional building machines were presented together with a live demonstration by Wojciech Staniszewski in the garden and auditorium of the Archenhold Observatory, Berlin (Fig. 6).
One of the most outstanding works welded with the machinery presented during this session was Leviathan, an inflated sculpture by Anish Kapoor at Grand Palais, Paris: https://www.youtube.com/watch?v=12Ni0c4D27Y

Figure 6. FIAB welding machine live demonstration at Textile Roofs 2017.

World Cup Membrane Structures.

Martin Glass, gmp Architekten. http://www.gmp-architekten.de

Martin Glass began by recalling the general philosophy of gmp Architekten designs summarized by simplicity, clear solutions, variety, uniformity, distinctiveness and structural order avoiding monotony. He profusely illustrated these principles and highlighted two outstanding examples: the Al Bayt Stadium in Al Khor City, Qatar and the new retractable roof for the Verona's Roman arena.
The Al Bayt Stadium in Al Khor City, Qatar design is based on the Bayt Al Sha'ar, a black and white tent used traditionally by nomadic people in Qatar as a welcome symbol of hospitality for desert travelers (Fig.7). Changes of scale, materials and building solutions are noticeable, particularly the trussed steel structure and air conditioning.

Figure 7. gmp Architeckten, 2022: Al Bayt Stadium, Al Khor City, Qatar.

The other example is a risky intervention on a historic building, the Verona Roman amphitheatre. An international competition was launched with demanding requirements. The controversial winner scheme is a 12.000m^2 foldable membrane sliding through a radial set of cables, hidden and stored beneath the compression ring, when not in use. The solution claims to be "a subtle intervention that will not take focus away from the architecture of the historical arena" (Fig. 8). But main unknowns are the compatibility between the structure required by such a roof and how its foundations should be executed without substantially affecting the existing building.

Figure 8. gmp & sbp, 2017: convertible roof over the Roman Amphitheatre, Verona.

Membrane structures in Russia

Vladimir Ermolov,
Moscow Institute of Architecture & Verteco.

The most comprehensive presentation of this edition of Textile Roofs was undoubtedly that of Vladimir Ermolov. A universe of membrane structures was shown starting from the antecedents found in ancient Russia icons and drawings. Before 1917, textile roofs were found in fairs, markets and circus tents. The outstanding case of early tensile structure engineer and architect was Vladimir Shukhov (1853-1939) for his steel tents at the 1896 All-Russia industrial and art Exhibition in Nizhny Novgorod (Fig. 9). During the last century there were no significant advances until 1991 with the reformation engaged by the Perestroika. It caused everyone to start their own firm. Starting from this period, the lecturer presented some of the works done by several companies and finally focused on his realizations with Verteco Co Ltd, Balashikha (Fig. 10).

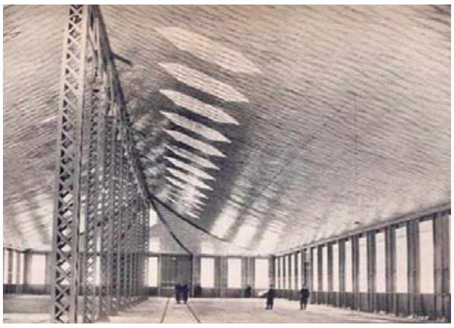


Figure 9. Vladimir Shukhov, 1896: Rectangular Pavilion at the All-Russian Exhibition, Nizhny Novgorod.

Figure 10. Vladimir Ermolov: Membrane structure in Russia made by Verteco.

Large-sized dome-shaped constructions.

Andrej Moroz, Lommeta, Novosibirsk.
http://www.lommeta.com/

Lommeta presents itself as a company devoted to unique challenges and innovative solutions that disregards the possibility of using the word "impossible". The presentation of Andrej Moroz was about to confirm such a daring assertion. Large-sized domes have been designed to cover neither more nor less than open pit mines to turn them into conditioned cities, recovering the 1960 idea of Buckminster Fuller for a two-mile-wide dome over Manhattan to save energy and make a better city. More realistic was the "Allianz Arena" style façade made of multi-layered ETFE cushions framed by tubular sections. And even more realistic was the automated solution for storage of equipment, vehicles and aircraft: a lightweight and robust aluminum frame lined with a high-strength architectural PVC material (Fig. 11).

Figure 11. Automated solution for storage by Lommeta.

Lightweight Membrane Structures postgraduate MEng programme

Robert Roithmayr, formfinder GmbH.
https://www.formfinder.at/

Robert Roithmayr presented the "Lightweight Membrane Structures" postgraduate MEng programme 2017 to be held at the Donau University Krems, for individuals working in the field of lightweight membrane structures and related fields, ranging from design and architecture, engineering, business administration, manufacturing, installation, textile industry and related sciences. The curriculum of the course includes guiding principles, architecture and engineering, tools for design, materials, details, management, manufacturing, installation and master's thesis. It is supported by "formfinder", the computer assisted design of Lightweight Membrane Structures, and its data bases. For the reasonable amount of €16.900, participants will join the professional team of experts and practitioners led by R.Blum, J.Hennicke, H.Dürr, and R.Roithmayr himself. They will be prepared for a rapidly changing and challenging future with new skills and experience. More information at: www.donau-uni.ac.at/dbu/membrane

Natural light, acoustic and thermal comfort in membrane structures

Farid Sahnoune, Serge Ferrari S.A.S.
www.sergeferrari.com

Farid Sahnoune addressed four challenges for membranes in architecture: durability, acoustics, thermal insulation and natural light. Regarding the durability, he presented the performance of the highly durable and recyclable "Précontraint TX30", a new generation of composite materials to match the requirements of the most demanding projects. This technology combines a Crosslink PVDF surface treatment highly resistant to photo-oxidation, a 30 year PVC coating formula engineered to resist erosion for more than 30 years and an outstanding dimensional stability thanks to the Précontraint technology. Accelerated ageing has been measured and correlated with monitored natural ageing.

Concerning the acoustic comfort, he introduced Batyline Aw with its calibrated micro-texture that ensures sound absorption, highly uniform acoustic behaviour and significant reduction in reverberation time. It can be adapted to slopes, curves, and complex shapes fulfilling the comfort requirements of buildings receiving the public. Its most outstanding application is the acoustic improvement of swimming pools, restaurants, sport halls, ice rings and the like absorbing, on average, 65% of the noise without the need for other absorbent materials such as mineral wool or plastic foam (Fig. 12).

Figure 12. Batyline Aw and Silcord swimming-pool tensioned ceiling.

Testing

Rosemarie Wagner
Karlsruhe Institute of Technology.
https://www.kit.edu

Professor Rosemarie Wagner started her lecture commenting on fundamental equations for numerical static and dynamic simulations (Fig. 13). She addressed then the uniaxial and biaxial testing of textile membranes exploring the effects of coating, directions of warp and weft, load speed, load ratios, cyclic loading, compensation values, creep, material constants, damping and fatigue to obtain estimations applicable to the numerical analysis. She finally presented the current research on folding and inflating membranes for tanks.

Figure 13. Dynamic simulation by J.Bender, Karlsruhe Institute of Technology.

TransProof. New opportunities for weather protection

Tobias Raithel, ETTLIN, Ettlingen.
http://www.ettlin-smartmaterials.de/produktlinien/transproof/

Since 2008 ETTLIN produces innovation products for application areas with a high change potential such as smart materials for lighting, electronics and architecture. The lecture was dedicated to the new development TransProof, a special fabric for outdoor shading presented by R.Wagner at textile Roofs 2016. T.Raithel introduced the advisable properties of textile shading systems as: good shading, low or no air permeability, no transparency, weather protection and waterrepellence. The new material TransProof adds to them protection against moisture and rain, good sight and cooling shadow without heat accumulation. The structure of TransProof is characterized by the grid of the fabric with narrow and elongated adjustable openings (Fig. 14), black colour (or customized from 2.000m^2), water-repellent, good transparency and air permeable. There are three independent thread systems with strength and strain properties adjustable in warp and weft directions with low deformations due to the straight yarns (Fig. 15).

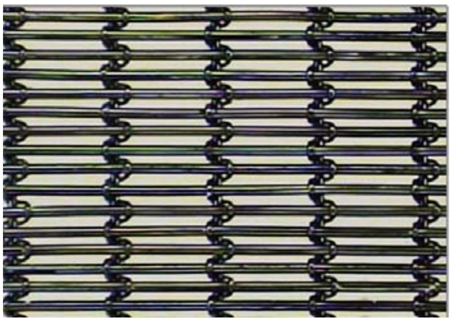


Figure 14. Structure of TransProof: a fabric with narrow and elongated openings.

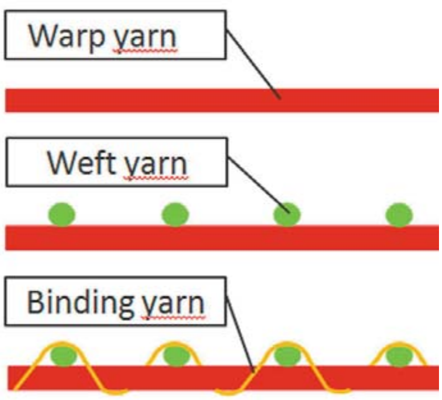


Figure 15. Three independent thread systems of TransProof.

Its suitability as a prestressed and curved textile membrane for outdoor shading has been thoroughly tested at the Karlsruhe Institute of Technology. The parameters for the load capacity, use, assembly and fixing have also been determined concluding that the fabric is quite suitable for the textile membrane construction. However, in designing the construction, the properties of the fabric must be considered and the assembly and fixing technology of the textile fabric may be performed with the classical procedures such as melting and sewing.
Finally, further development of TransProof was envisaged consisting of customizing the tightness and porosity by means of an adjustable special water-repellent finish. Thus, the respective properties such as shading, air permeability, transparency and water-repellence can be adjusted in each direction.

Wind membrane interaction

Alexander Michalski, str.ucture GmbH, Stuttgart.
http://www.str-ucture.com

After a philosophical approach, Alexander Michalski presented a fluid-structure-interaction simulation suitable for highly elastic membrane structures, such as applications where the structural response of wide span membrane structures is affected by added mass and damping effects of the surrounding air. This methodology has been developed by str.ucture especially for lightweight structures and validated at a real-scale test of a 29m umbrella prototype in cooperation with SL.Rasch. Among other examples, he commented on the Norway pavilion for the Shanghai Expo supported by 15 tree elements made of laminated timber spanned by a PTFE membrane. The membrane covers an area of 2.500m^2 with a maximum span of 11m (Fig. 16).

Figure 16. Helen & Hard, 2010: Norway Powered by Nature pavilion, Shanghai.

Tensile structures in India, Abdul Sathar,

nospan Structures Pvt Ltd. Bangalore.
www.technospan.co.in

Before entering the membrane structures in India, Abdul Sathar introduced a short history of roofing systems in India with straws, coconut leaves and clay tiles (Fig. 17). Membrane structures were first implemented in India in automobiles and tents. Textile roofs started being executed in 2004. There were less than 2 or 3 companies until 2008. Today there are more than 150 companies but only 5 in grade A fully integrated. Most of the structures are designed without any engineering with prices that

Figure 17. Roofing system with straws, India.

start from €30 - €100 for the complete structure (?). Failures are common due to poor engineering and bad detailing aggravated by the stormy weather. Fortunately, the company Technospan, with a history of 18 years in the field of roofing structures in India, bought in 2007 the "Easy" suite of programmes and met Matti Orpana (Fig. 18).

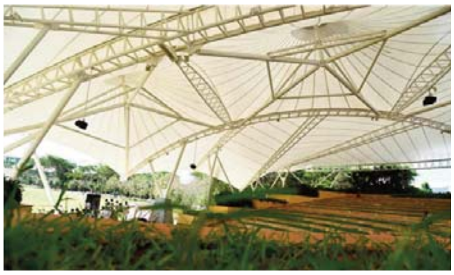


Figure 18. Technospan, 2015: Infosys Chennai Amphitheatre.

Temporary structures / Circus tents

Rogier Houtman, Tentech BV, Utrecht.
http://tentech.nl

Rogier Houtman started showing some historic temporary structures, particularly hangars and circus tents as an introduction to his own works as a leader of Tentech, an innovative design and engineering consultancy founded in 1997 as a spin-off from the Faculty of Civil Engineering at Delft University of Technology specialized in lightweight structures. Their architects and engineers focus on membrane structures, temporary structures, complex geometries and the use of distinctive materials (Fig. 19). In addition to fabric, steel, wood and aluminum, Tentech explores the implementation of cardboard, synthetic materials and bamboo.

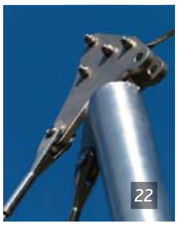
Figure 19. Special Tentech structure. Rose Garden. Tomorrowland 2016.

REPORT

Joint participants' project

Stev Bringmann, 3dtex GmbH
http://www.3dtex.de

A four point sail was designed and erected by the participants led by Stev Bringmann and Jürgen Hennicke with the collaboration of Serge Ferrari, Karsten Daedler e.K., FIAB, Pfeifer Seil und Hebetechnik GmbH and technet GmbH. The entire manufacturing and installation process was carried out (Fig. 20 to 25). Phases involved were: "easy" modelling (form finding, structural analysis, and patterning), manufacture, foundations, assembly (masts, edge cables, corner plates, erection, and tensioning), and discussion.



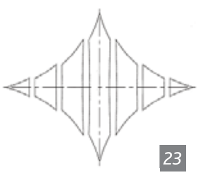


Figure 20. Form finding by physical modelling
Figure 21: Erection of masts.
Figure 22: Top of the mast detail.
Figure 23: Cutting patterns.
Figure 24: Corner.
Figure 25: The four point sail completed.

Textile Roofs 2018 will be held on 15-17 May 2018. Its format will be similar to that of TR 2017, with seminar-style lectures and hands-on activities. It will be preceded by the student seminar and sponsored by Serge Ferrari, Pfeifer and technet, and supported byTensiNet, KIT and gmp.
http://www.textile-roofs.de

Josep Llorens
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ARTICLE

NON-LINEAR ANALYSIS SOFTWARE FOR MEMBRANE STRUCTURES

Introduction

In the analysis of traditional building structures, we tend to use linear calculation. What does this mean? It means that results (reactions, stresses, displacements and deformations) are proportional to loads (actions).

So, if we get a 3mm deflection on a steel beam when we apply a load of 50kN, no need to re-calculate to find out what will be the deflection of the beam in the case we apply a load of 100kN. It will be 6mm. And if the load is -50kN, then the deflection will be -3mm. This is the basic concept of linear analysis.
But there are cases which behave differently. In these cases, we use a **non-linear analysis**, also called **second order analysis**. And tensile structures is one of them. There are various types of non-linearity. We are going to comment on the four most common ones.

1. Geometric nonlinearity: The movement of a structure is very large and balance depends on the final form which is unknown.
2. Mechanical non-linearity: Elements. Some parts of the structure “disappear” during the deformation. For example, cables that get shorter.
3. Mechanical non-linearity: Materials. Some materials behave differently as they deform.
4. Mechanical non-linearity: Loads. Some live loads (wind, snow…) change if the shape of the structure changes.

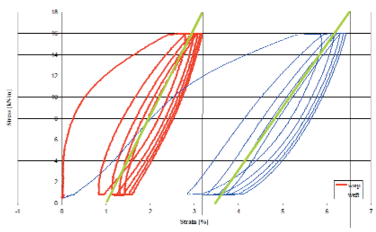


Figure 1. Example of a stress-strain graphic.

A simple example of previous point 3 can be found to obtain the modulus of elasticity of a typical membrane used in textile structures. Stress-strain graphics are complex and depend on many factors: type of biaxial load, load history, etc. (Fig. 1)
A more detailed information at:
http://www.wintess.com/modulo-de-elasticidad-de-una-membrana/

In all these cases, analysis is made in an iterative way. This means that after calculation balanced forces are checked. If the structure is not balanced we calculate again using unbalanced forces. And we must repeat this procedure as many times as necessary until we get balanced forces for the corresponding deformation. If forces are balanced quickly we say that the procedure has good convergence. On the contrary, if it takes a lot of iterations to get balanced forces or it never happens, the procedure has very bad convergence or no convergence.
Most of the times, a bad convergence means an unstable structure, at least under the loads applied. Of course it might be a problem of the procedure (software), but if so, bad convergence would appear in all cases.
(http://www.wintess.com/calculo-no-lineal/)

Integrated calculation

One of the advantages of non-linear analysis is that studying complex structures (formed by clearly differentiable parts) is possible in a single unit. In most of cases this results in a more economical structure and, mainly, in a more precise analysis.

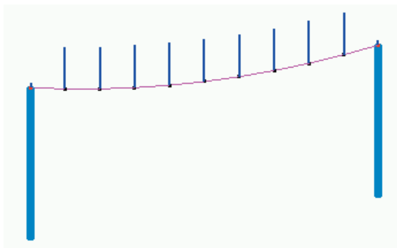


Figure 2. Analyse of cable structure - forces.

To illustrate this problem, we will perform the calculation of the following structure: Structure to be analysed: It’s a 10m chord cable, 50cm sag, hanging from the top of two columns formed by steel tubes. A load of 5kN/m is applied on the cable, so there are 9 forces with a total of 45kN (Fig. 2).

Cable analysis is very easy, even manually. We get reactions at both ends: vertical (half the vertical loads) and horizontal depending as well from sag. With these

WINTESS

reactions, columns can easily be calculated in compression (vertical reaction), shear (horizontal reaction) and bending (column height and horizontal reaction). So, why should we apply a non-linear analysis?
When we analyse the cable with a more focused approach (manually it is very difficult) we get not only vertical and horizontal reactions but also a deflection which has to be added to the sag (Fig. 3). So a new sag is obtained, and automatically new reactions (in fact only new horizontal reaction) are to be considered. If we reproduce this procedure until the new value is practically the same as the old one (convergence), we will get reactions that are smaller than the first ones. It implies a smaller cable (less self-weight, so less total vertical load) as well.

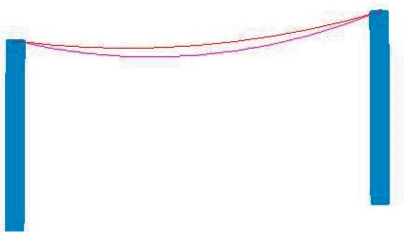


Figure 3. Analyse of cable structure - deflection.

If these reactions are smaller, analysis of column will be different too. The less horizontal reaction will lead us to less shear and bending stresses. This will yield a reduction of the column size, since bending is for sure the most demanding effect on a column. If we want to be picky, even vertical reaction, which is always practically the same (only cable self-weight changes), will be modified using P-delta analysis method. Vertical reaction and displacement of the column head will produce a small bending moment which needs to be added to the principal bending moment. If we analyse this structure as a single integrated structure, all these factors are taken into account and results are clear:

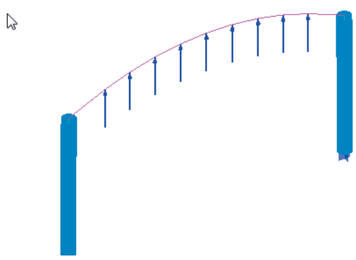
- Manual analysis:
  Steel cable 1x37 diameter 20mm
  Steel tube S355 Ø500.12 (diameter 500mm, thickness 12mm)
- Integrated analysis
  Steel cable 1x37 diameter 18mm
  Steel tube S355 Ø470.10 (diameter 470mm, thickness 10mm)

(http://www.wintess.com/calculo-integrado/)

Safety Factors and Combinations

Linear analysis is widely used for Combinations. If we assume that results (reactions, displacements, stresses…) are proportional to actions (loads, temperature, forced displacements of supports…), then we can analyse a set of load cases and combine their results applying factors to each case to form a set of loads combinations. Unfortunately this is not possible in non-linear analysis.
Just imagine the same structure we have analysed in the previous section 2 of this text: Two columns supporting a "horizontal" cable with a uniform load on the cable. Now loads are "negative" (Fig. 4).

Figure 4. Analyse of cable structure – "negative loads".



It is very easy to see that if we change load direction (factor = -1), what we get is:
Deformation of the cable is just the opposite
  → = -1
Tension of the cable is the same → = 1
Axial load of the columns is the opposite
  → = -1
Shear forces and bending moment of the
  column is the same → = 1
Main forces at the footing (bending moment
  and Fh) are the same → = 1,
  while Fv that is not so important is the
  opposite → = -1

As we can observe, this represents a chaos and it is obvious that we cannot use the loads combination procedure we typically use in normal architectural structures. What we must do is to combine all the loads in a single case and analyse it. Results are unpredictable. Then, when we have the outputs of loads combinations, we can check which the worst case is. It may not be (most probably) the worst combination of loads.
If loads combination is an issue, using safety factors is at least as much problematic as this. Safety factor is applied to material resistance and to loads. In linear analysis we can analyse the structure with a factor applied to the loads, according to the rules (standards, codes…). But we can also analyse the structure with loads without safety factor and apply this safety factor to the results. It's just the same. But as we have seen, this is not applicable in non-linear analysis.
If we apply a safety factor to the loads (as many codes recommend), results will be different from what we would get if we applied the real load and then introduced the safety factor onto these results.
Which is the correct procedure? There are different opinions on that. But what we prefer is to analyse the structure with the real load (without any safety factor) and when we get the results, then we apply the safety factor to these results. This way behaviour of the structure is not affected by an "artificial" load created with the real load modified by a safety factor.
But, of course, the opposite could be also true. Safety factor on loads means that loads could be higher than those proposed. So, if we apply these higher loads we would get a possible real case.

Fortunately, things are not black or white. There is a long range of grays.
And in many cases non-linear behaviour of a structure is very close to linear behaviour. When this happens, there is practically no difference between applying safety factor to the loads or to the results. Only in some very particular cases these two methods could be very different.
A more detailed reflection on this problem can be obtained at http://www.wintess.com/coeficientes-de-seguridad-y-combinaciones/.

WinTess software uses nonlinear analysis and takes benefit of most of the points commented in this text. Non linear analysis is a must for tensile structures, and it should be seen as an advantage rather than a disadvantage. At least that's what we feel when creating and improving the WinTess software.

Prof. Ramon Sastre &
Dr. Xavi Gimferrer,
ETS Architecture Vallès, UPC WinTess
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http://www.wintess.com/

ROOFING CHILDREN´S PLAYGROUND & NATIONAL DAY STAGE

Astana, Kazakhstan

For the first time the world exhibition Expo 2017 takes place in Kazakhstan. Themed as "Future Energy: Action for Global Sustainability", an exhibition of superlatives is being built on a 113 hectare large site. Large and small objects form a breath-taking ensemble of modern architecture.

Flower pavilion

One of the smaller pavilions is the so-called "Flower". A canopy for a children's playground in the middle of the Expo area. A small construction, that consists of a prestressed, interrelated curved membrane, which bears on six curved, circularly arranged, two-hinged frames. The outer base points of the steel arches are mounted on individual basements. The base points in the middle on a common foundation. The roof skin consists of a PVC-coated polyester fabric. The membrane lies along the arches and will be stretched downwards by border cables (Fig. 1 and 2).

Figure 1 and 2. Children's playground canopy.

Name of the project:	Flower EXPO 2017 Astana
Location address:	Astana, Kazakhstan
Client (investor):	Expo 2017
Function of building:	Roofing children's playground
Type of application of the membrane:	tensile roof
Year of construction:	2017
Architects:	Michael Kiefer (K.TA)
Structural engineers/ Detailed engineering:	Kathrin Kaltenbrunner (K.TA), Manfred Schieber (K.TA)
Consulting engineer for the membrane:	Tobias Ludeke (K.TA)
Main contractor:	APS Engineering
Contractor for the membrane:	APS Engineering
Supplier of the membrane material:	Ferrari
Manufacture and installation:	HP Gasser/ APS Engineering
Material:	PVC
Covered surface (roofed area):	ca. 80m²

National Day Stage pavilion

A second pavilion is the "National Day Stage". A stage roof with auditorium, which is located in the immediate vicinity of the focal point - the Kazakh pavilion "Nur Alem". The supporting structure consists of five semi-circular, polygonal curved trussed beams, in which the radius of the beams decreases from the centre towards the outside beam. The trussed beams are connected and stiffened by compression struts. As it is a temporary construction, the loads are removed by means of concrete blocks, which are laid as a foundation under the entire structure in a grid-like manner. The stage area is divided into an outer and an inner stage area. The exterior measures 17mx22.5m, with a maximum height of 10.5m.

The inner, smaller stage area measures approx. 10mx15m. Thus allows the artists, property-masters, organizers, etc. to separate into areas "before" and "behind the scenes". The upstream auditorium provides protection for the viewer. The roof skins of all three areas are made of a PVC-coated polyester fabric. In the stage area, the membrane is placed transversely over the beams and fixed linearly to the edge beams. In the area of the auditorium, the membrane is also attached linearly to the main support of the stage area and anchored to the outside by edge cables and anchoring columns on the grid.

Figure 3. Top view stage and auditorium.
Figure 4 and 5. Side view day – night.

Kathrin Kaltenbrunner
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www.k-ta.de

Name of the project:	National Day Stage EXPO 2017 Astana
Location address:	Astana, Kazakhstan
Client (investor):	Expo 2017
Function of building:	Stage roof with auditorium
Type of application of the membrane:	tensile roof
Year of construction:	2017
Architects:	APS Engineering
Structural engineers/ Detailed engineering:	Tobias Ludeke (K.TA), Manfred Schieber (K.TA)
Consulting engineer for the membrane:	Tobias Ludeke (K.TA)
Main contractor:	APS Engineering
Contractor for the membrane:	APS Engineering
Supplier of the membrane material:	Ferrari
Manufacture and installation:	HP Gasser/ APS Engineering
Material:	PVC
Covered surface (roofed area):	400m²

THE BRONTE PARK AMPHITHEATRE
A NEW WATERFRONT ICON

Oakville, Canada

Context

The Bronte Park Amphitheatre structure is a multipurpose pavilion in Bronte Heritage Waterfront Park in the Town of Oakville, a suburb of Toronto. The Bronte Heritage Waterfront Park is a popular destination for tourists and locals and features an active marina, conference centre, fisherman's wharf and green space. The amphitheatre will provide an outdoor performance venue as well as shelter from rain and shade for respite and picnics etc. It's dramatic and iconic form will be highly distinct and recognizable and is expected to make it popular for landscape and wedding photography.

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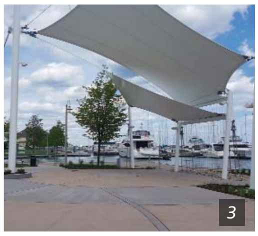

3

Project

The sailing culture of the marina is a dominant feature of the park and a nautical aesthetic was an objective for the amphitheatre structure. Stainless steel marine cables and fittings have been used extensively. The main mast was detailed deliberately to resemble the mast of a sailing ship and the spreader beam intended to invoke a nautical spar. A stainless steel cable screen provides a backdrop for the stage. The cables are tensioned between a French drain at grade and the troughs above into which rainwater is channelled. This feature manages rain splash in summer and will accrete ice in the winter creating a sparking translucent curtain. It also provides an opportunity to hang banners or support climbing plants.

Clients request and projects purpose

The Bronte Park Amphitheatre fulfils a number of functions within the park. First and most explicitly it is an event space. The fabric provides 1.000 sf of shelter from sun, snow and rain for performances in the park. The superstructure has been designed with a series of 2.000 lb "pick points" to suspend rented lighting trusses and audio visual equipment. The cable screen provides an opportunity for a back drop.
The structure is also an iconic and recognizable form that responds to the harbour and marina and will become a symbol for the park and the Oakville Waterfront. It will be a destination for visitors seeking shelter or taking pictures.

Uniqueness

This project has incorporated a number of unique and complex elements in fulfilling its function. Two membranes overlap to form the structure rather than a single covering membrane. The overlap was carefully considered to maximize rain protection while allowing light through to maintain a bright open space and create visual interest. The spreader beam, which supports the outstretched wings of the membranes, floats in a cable net in a tensegrity fashion, rather than connecting to the mast. This presents challenges both from a structural design and analysis standpoint and to the erector but give the structure a sense of "look ma no hands" magic. The apparently symmetric structure is asymmetric to allow the membranes to overlap. This along with the floating spar resulted in an extremely complex geometry, both from a detailing and fabrication point of view.
A pair of troughs, fabricated from bent plate, does dual purpose: accumulating rain water from the two membranes and providing the tensioning boundary for the stainless steel screen. The screen itself is unique in its ambition to create ice in the winter and form a glassy curtain. The foundations are possibly the most unique and complex part of the project. Rather than large discrete concrete footings or grade beams, the foundation is entirely made of galvanized steel. Large beams connect the mast and stays making the structure a "closed" system. The ends of the interconnecting beams are supported on steel sleepers which spread the load onto the native fill material. The use of steel foundation allowed the below grade work to be completed extremely quickly, in just a matter of days, to accommodate an ambitious schedule. It also ensured that base anchors for the mast and stays would be accurately located to minimize site adjustment and rework for the structure. An analysis was undertaken to ensure that the longevity of the buried steel would be consistent with the intended design life of the project.

A new waterfront icon

Within days of the erection of the structure, many weeks before the opening of the project, the Town of Oakville began receiving requests for permits to use the site for wedding photography. As a waterfront icon, the project had already made its mark.
The first major event was July 1, 2017: a Canada Day celebration for Canada's sesquicentennial, being called the Canada 150 celebration. After a series of day time family concerts the stage was occupied by tributes to two iconic Canadian bands, the Guess Who and Supertramp. It also provided context for a spectacular fireworks display (Fig. 4)!

4

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http://tensileintegrity.com

Figures 1 to 3. Project seen from different angles.
Figure 4 . Canada 150 celebration: day atmosphere.

Name of the project:	Bronte Park Amphitheatre
Location address:	Oakville, Ontario
Function of building:	amphitheatre
Year of construction:	01.05.2017
Architect:	EDA Collaborative Inc., Patrick Li
Design:	Blackwell, David Bowick
Engineer:	Blackwell, David Bowick
Project Manager:	Town of Oakville, Rakesh Mistry
Contractor:	Cambium Site Contracting, Frank Williams.
Supplier & producer of the membrane material:	Ferrari S.A
Fabricator:	Soper's/Depco, Lincoln Gallagher & Derek Penney
Subcontractor:	Tensile Integrity, Jamie Gallagher
Installation:	Depco, Derek Penney
Material:	Precontraint 1302
Covered surface:	280m^2

KINEMATIC FORM-ACTIVE STRUCTURES FOR ARCHITECTURAL APPLICATIONS

Design, Analysis and Experimental Verification

Due to their low self-weight and their inherently high flexibility, lightweight technical textiles offer great possibilities for the integration in kinematic structures. Furthermore, new interesting typologies combine the use of mechanically prestressed membranes with the lightweight principles of active bending. Integrating these principles in a transformable design creates challenging perspectives, exploring the great variability in possible geometries and expressive shapes. Unfortunately, until now, there is still a lot of research to be covered on the material properties of technical textiles, their structural behaviour during deformation and the use of available design tools. Also for the design and analysis of textile hybrids many research is still ongoing and, furthermore, the interaction between the bending elements and the membrane complicates the integration of the kinematic aspect. Up to the present, the inability to keep the fabric properly pretensioned in all deployment stages within the structure's limitations obstructs the use of fabric structures for kinematic applications (like e.g. as an adaptable façade shading system as presented in Fig. 1).

The challenge of this research was to obtain (two) transformable systems for kinematic applications in which the membrane prestress is controlled throughout all the folding states of the structure. The aim was thus to keep both the membrane and the supporting structure stable in the different phases of the deployment. Through the analysis of case studies, the main research question is aimed to be answered: «Can the integration of technical textiles in kine(ma)tically deployable structures result in an efficient transformable lightweight structure, remaining tensioned in all configurations of the application range?»

This article is based on the research presented in the doctoral thesis [1] and describes the design, analysis and experimental verification of two selected case studies in order to prove the feasibility of designing kinematic form-active structures and confirming both the possibilities and the remaining challenges. More detailed results can be obtained by consulting the thesis manuscript and in the journal papers [2] [3], where the results of case study 1 are discussed thoroughly. The results of case study 2 will be presented in two other journal papers.

Two representative case studies

The first case study consists of a membrane that is tensioned in a transformable frame. Opening and closing the frame results in unfolding and folding the membrane. As the deployment is established through the rotation of rigid hinged angulated beam elements (i.e. a rigid body motion), this case is classified under 'rigid hinged boundary kinematics' (Fig. 2 - left). The second case study investigated in this research consists of a (quasi-) self-supporting structure with a flexible membrane that is tensioned in a bending-active ring element and will be referred to as 'bending-active boundary kinematics' (i.e. elastic kinetics). By applying a certain prestress on the membrane, the originally flat structure pops up to a three-dimensional shape. This form-found geometry is then used as a starting position of the kinetic deployment (Fig. 2 - right).

To be able to provide a clear answer to the main research question, also a number of important sub questions is aimed to be answered:

How will we simulate these KFAS? *To what extent can an analysis tool used for the analysis of tensile surface structures be used to model different configurations of the kinematic form-active structures (KFAS)?*

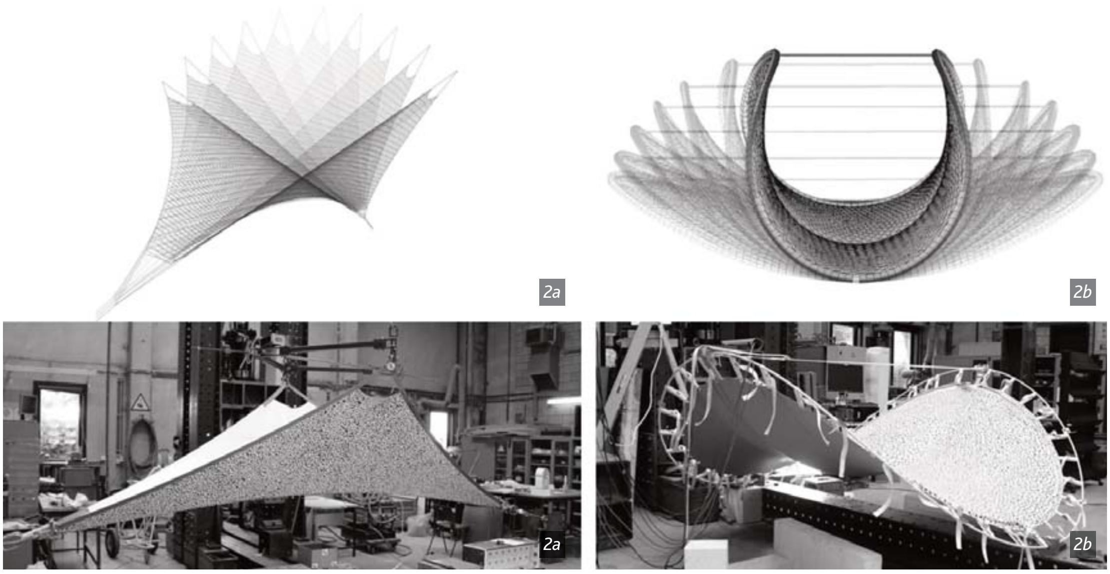


Figure 1. Conceptual visualisation of a kinetic facade system integrating a mechanically stressed membrane.
Figure 2. Numerical and experimental models of: (left) Case study 1 – rigid hinged boundary kinematics; (right) Case study 2 – bending-active boundary kinematics.

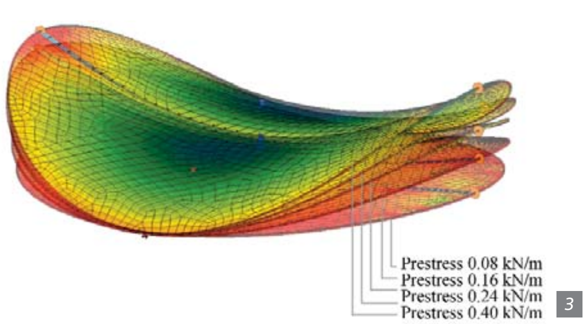
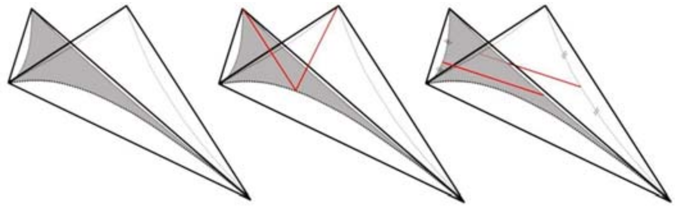


Figure 3. Case study 2 - The applied prestress determines the three dimensional shape of the pringle-shaped textile hybrid.



	Area (m²)	Height (mm)	Width (mm)
10°	2.91	1346.1	2833.9
30°	2.92	1347.0	2831.7
50°	2.91	1350.5	2822.5
70°	2.91	1364.2	2803.3
90°	2.90	1397.4	2763.3

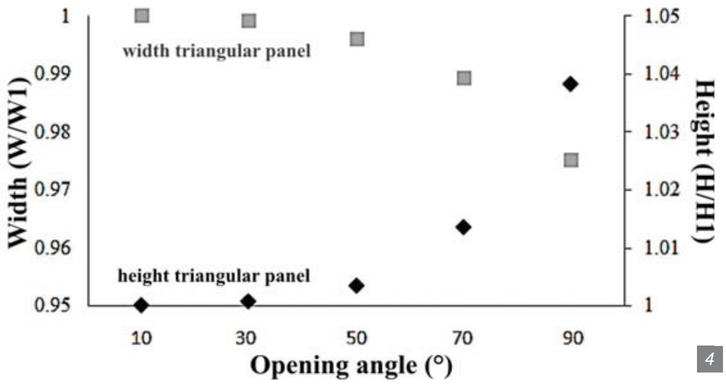


Figure 4. Case study 1 - The geometry changes throughout the deployment: increase in height (H/H1) and decrease in width (W/W1) with increasing opening angle.

The thesis discusses how a simple linear elastic numerical model can serve as a valuable design tool both for the form-finding and for the simulation of the kinematic deployment.
The first case study is modelled in Easy© [4], where the membrane surface is approximated by a cable net. The Easy software is specifically developed for the design and analysis of membrane structures and uses a linear elastic material model, integrating the shear stiffness and the effect of crimp interchange. In the second case study, bending-active elements are integrated in the kinematic membrane structure. As Easy cannot cope properly with those bending elements, new options are explored. Therefore, the Finite Element software Sofistik© [5] is used to model the textile hybrid, where the membrane is simulated as a continuous surface. Also here a linear elastic material model is implemented. Both software programs allow implementing a geometrically nonlinear calculation and have an integrated cutting pattern generation tool.
Even to model the simple linear elastic material behaviour a correct determination of the material properties is of major importance. The kinematic aspect of the membrane structures adds an extra dimension. For the PVC-coated polyester membrane (case study 1) both a standard MSAJ biaxial test was performed and a tailored biaxial test that mimics the behaviour of the kinematic deployment of the KFAS (where the biaxial load profile is based on the stresses in the large-scale numerical model). The observed difference confirmed the importance of a project oriented biaxial load protocol and thus the importance to approximate the material behaviour as close as possible. For the PU-coated fabric (case study 2), the limits of the biaxial bench at the Vrije Universiteit Brussel unfortunately didn't allow a project oriented biaxial test (due to the high deformations and the low applied loads) and thus only a standard biaxial test was carried out.
The form-finding under the applied prestress occurs in Easy through the force density method, whereas Sofistik uses the reduced stiffness method for the form-finding of the membrane. The high deformations of the bending-active boundary elements complicate the numerical modelling and therefore a slightly adapted form-finding process is adopted compared to traditional membrane structures. In this second case study, the geometry changes significantly with increasing prestress (Fig. 3).

The kinematic deployments of the structures are modelled as an analysis under external loading that is applied on the form-found geometry. Both software packages allow an iterative calculation process, whereby the relative deformations, forces and strain variations can easily be compared for different opening phases.
In order to verify the accuracy of the numerical models, experimental investigations serve as a validation of the simulation process. The experiments showed that the results derived from the numerical model give a good approximation of the experimentally obtained results and confirm thus that the simple linear elastic material models allow a good prediction of the actual behaviour of the membrane structure. More information on the experimental investigation is given further in this research article.
However, an important point of concern is that the linear elastic model does not take into account the large initial and permanent deformations of both the membrane and the polyester belts. It is confirmed that a correct derivation of the compensation factor is of major importance, as deviations in the used cutting patterns influence both the form-finding geometry and the behaviour during the kinematic deployment.

How do we design KFA? *...to keep the membrane tensioned in all its phases of the considered transformation. In other words, which design parameters and values can improve the overall structural response in various configurations?*

This research proves that an exhaustive preliminary numerical study is essential to enhance the overall structural behaviour of the membrane structure in all stages of its transformation (within the application range), keeping the membrane properly tensioned and avoiding excessive stress concentrations. As the design and analysis of KFAS is quite new, these parameter studies clarified some important steps that need to be integrated in the design process.
For both case studies a parameter study was performed to derive a set of conceptual design considerations for the kinematic prestressed fabric structure. The specified parameters to be verified in the design process were (i) the boundary configuration in which form-finding was conducted (i.e. the reference state), (ii) the prestress levels and ratios, (iii) the control of the deployment and (iv) the used material parameters and dimensions of the elements. Note that for the case study with integrated bending-active elements (i) and (ii) are directly related, due to the high interaction between the boundary and the membrane.
Compared to the design of traditional membrane structures, the choices of the above mentioned parameters do not only depend on the structural behaviour under external loading, but also on the behaviour of the kinematic deployment.
For example, the geometry of the membrane in case study 1 changes when folding and unfolding the structure (Fig. 4). This results in varying strains and stresses of the membrane material. It thus needs to be verified that the membrane remains tensioned in the different phases of the deployment.

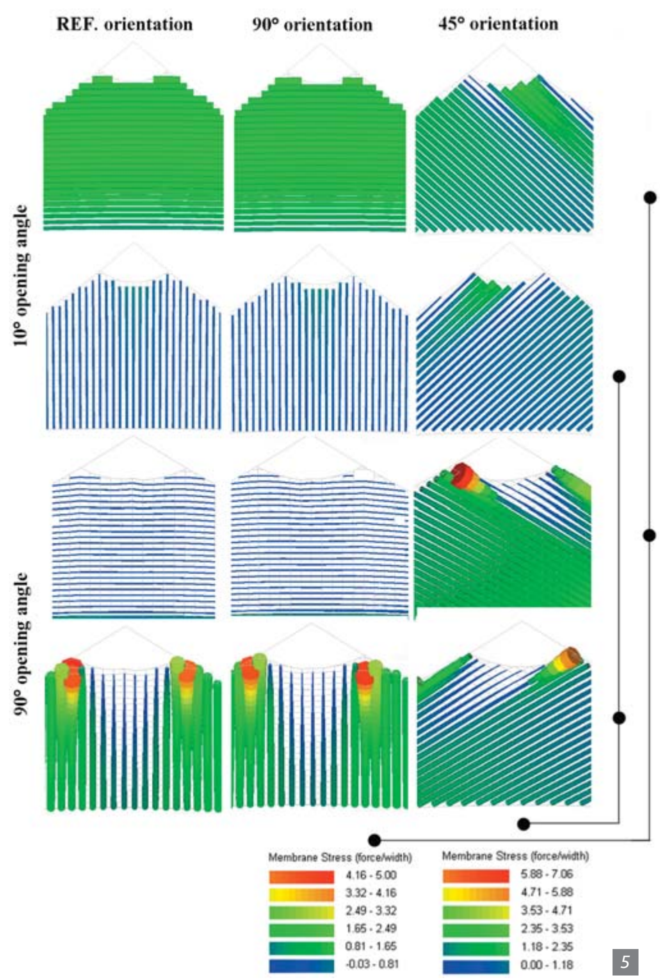
The influence of each of the selected parameters is investigated by varying every parameter separately. Both the form-finding state and the kinematically deformed configurations are studied in order to quantify the effect. Therefore, the stresses in the membrane in both warp and weft direction are compared, in order to select the conditions where the prestress is preserved the best in all the phases of the deployment. Other criteria for choosing a certain design parameter are for example the ease of prestressing the membrane and kinematically deploying the structure. As an illustration, the membrane stresses in warp and weft direction of case study 1 are presented in Figure 5, comparing different fibre orientations. More detailed findings on both case studies can be found in the thesis manuscript.

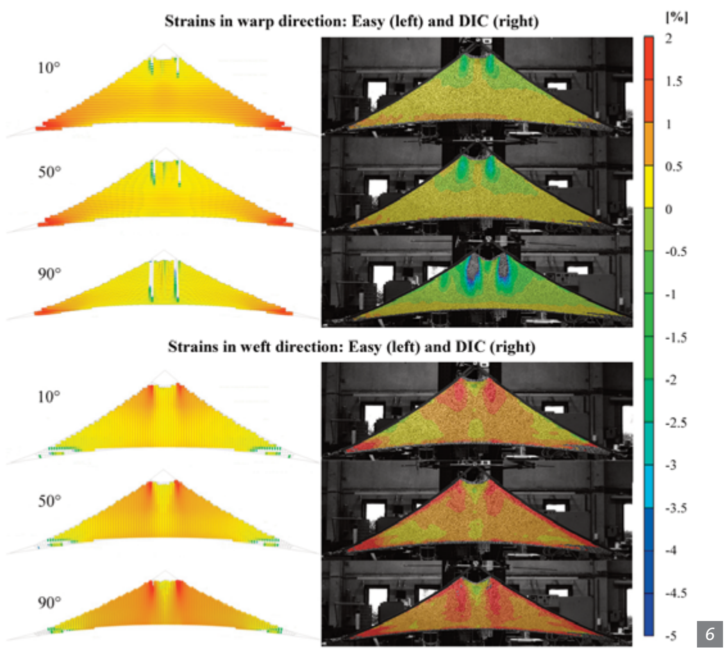
The analysis of this parameter study confirms that for kinematic form-active structures a whole series of possible combinations has to be investigated because one needs to take into account different phases of the structure's application range. The process of designing KFAS is thus clearly an iterative process, which underlines the advantages of using simple linear elastic numerical models. The available basic material models allow to change and adapt material properties, structural choices and geometrical data easily and quickly. For this type of preliminary design studies they prove to be an interesting tool.

Can this behaviour be confirmed by experimental validation? *Does the experimental data validate the numerical simulation, i.e. can we use this simplified simulation tool for the preliminary design of KFAS?*

The described parameter study leads to a 'final' design for each of the case studies, i.e. with an improved structural behaviour. For each case study a large-scale experimental set-up is then constructed and tested. The rigid hinged membrane structure has dimensions of ~6m by 1.5m, whereas the pringle-shaped textile hybrid has a diameter of ~3.2m. Displacements of the overall structure, strains in the membrane (in both warp and weft directions) and forces in the boundary elements are experimentally measured and compared to the results obtained from the numerical analyses.
Initially, the overall structural behaviour and measurements of the experiment show the same tendencies as the numerically predicted ones, however, the actual values of forces and strains showed some deviations. After further investigation of the experimental models, it became clear that those deviations occurred due to the application of inaccurate compensation factors. In case study 1, the large (elastic + permanent) deformation of the belts was not taken properly into account, whereas for case study 2, the membrane was overcompensated due to the impossibility to perform a project oriented biaxial test (as the limitations of the biaxial bench were reached). A re-calculation of the numerical model with adapted cutting patterns (membrane) or lengths (belts) confirmed the importance of using the right compensation factor, as these adapted numerical models showed an improved correspondence with the experimental results, both on the global level and on the level of actual strain values, displacements, forces etc. Figure 6 compares the strains measured with Digital Image Correlation [7] to the numerical strains from Easy.

The experimental investigation not only confirms the reliability of the numerical design models, but also involves a better understanding and some practical insights in the behaviour of the transformable membrane structures.





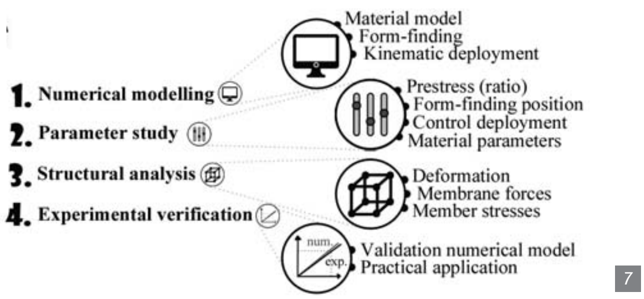


Figure 5. Case study 1 - Membrane stresses (kN/m) in warp and weft direction oriented following the reference, rotated 90° and rotated 45°. The results in 10° and 90° opening angle are shown, starting from a form-finding at 50° with a prestress of 1 kN/m in warp and weft direction.
Figure 6. Case study 1 - Comparing the experimental strain fields (measured with Digital Image Correlation) to the numerical results (derived from Easy) in both warp and weft direction.
Figure 7. Different steps in the "Design, Analysis and Experimental Verification of Kinematic Form-Active Structures (KFAS)".

Compared to traditional building components, the high membrane flexibility implies that every small (construction) detail can have a great influence on the actual behaviour.
This integrated analysis confirms the feasibility of creating kinematic form-active structures and the suitability of the used simplified numerical models to design those structures. The different steps of the analysis comprise generating an appropriate numerical model, performing a parameter study, carrying out a structural analysis and validating the numerical models by means of an experimental analysis (scheme shown in Fig. 7). This combination of numerical and experimental analyses definitely contributed to the overall understanding.
Although every type of structure will have its unique solution and this research thus not provides an overall design guide, this study provides an overview of some interesting insights and some important parameters to consider during the design of kinematic form-active structures. In what follows, some general conclusions are formulated that can be used for further investigation.

General guidelines

Case Study 1 showed some great opportunities of kinematic form-active structures for the integration in different applications: from transformable roof cover to kinematic façade shading… Some general thoughts can be summarised in order to extend the use to other geometries and sizes of transformable membrane structures. For now, this generalisation is restricted to membrane structures where the deployment results in a limited variation of the overall geometry, i.e. a variation in length of the principal axes of the membrane of ~0 to 5%.
Based on a study of geometrical variations, it can be concluded that increasing the prestress in the direction where the length decreases (the most), results in a more homogeneous stress distribution throughout the deployment. Depending on the amount of length variation, the prestress ratio between warp and weft direction can vary (e.g. opting for 1 kN/m in warp direction and 1.2 kN/m in weft direction, instead of 1 and 2 kN/m). If the change in lengths is too high, one could implement additional compression or bending elements, like is the case in the Soft House[6].
Also the choice of the form-finding position could be related to the variation in lengths during the deployment. One could select the opening angle that provides a compromise between the reduction in length in the one direction and the increase in length in the other direction (Fig. 4), in order to find the middle ground between stress increase and decrease when opening and/or closing the membrane.
In transformable membrane structures, the force-controlled connections could help to keep the membrane tensioned in the different phases of the deployment and avoid stress concentrations. In the Soft House, for example, a relatively simple system is designed to control the tension, using bending-active plate elements. Another way to obtain more homogeneously distributed stresses throughout the deployment is to align the 45° direction along highest loading directions, which provides more flexibility. In future investigations, one could use an uncoated mesh instead of the used PVC-coated polyester membrane (e.g. for façade shading).

Case Study 2 brought the design and the kinematic deployment to a next level. Not only the large deformations of the membrane material were important, but also the flexibility of the integrated bending-active elements played a crucial role in the design and experimental investigation of the kinematic textile hybrid. The important interaction between the prestressed membrane and the bending-active boundary elements complicated both the selection of the parameters and the interpretation of the results. Nevertheless, generalising some findings could extend the use of textile hybrids for transformable architectural solutions to other geometrical shapes and sizes.
A first step is to estimate the configuration and the zone with the highest beam curvature, which could occur either in the form-found position or in one of the transformation phases. Based on this curvature (and the selected material properties of the beam elements), the section can be chosen depending on the resulting initial stress. Next, the prestress in the membrane can be increased (i) until the intended geometrical shape is obtained or (ii) until the prestress value exceeds the acceptable range for the selected beam section. Combining different bending-active beam sections allows further increasing the prestress, as this increases the overall structural stiffness. Finally, the zones or directions where the highest loss of tension occurs can be reinforced with one or more internal elements.
Adding internal beam elements, on the one hand, contributes to the maintenance of lengths of the membrane but, on the other hand, also provides additional structural stiffness. Future research could investigate whether one has to add additional internal elements (in this case e.g. running from one lower point to the other lower point) to also preserve the length in this direction or whether other configurations of internal elements could provide better results. The latter leads us to the opportunities of using a knitted membrane material that allows integrating different materials and knitting types in order to (locally) change the membrane stiffness.

To conclude, it can be stated that although this study indicates the great potential of kinematic form-active (hybrid) structures, it only forms the first step towards an even more varied use of textiles in architecture. Thanks to the combination of the numerical analyses and the experimental investigations new interesting insights are revealed in the structural behaviour of both the case studies.

Acknowledgements

The researchers would like to thank Sioen Industries for providing fabric material for the experimental investigation and Carpro for the assembly of the large scale membrane. Furthermore, the authors would like to thank the Research Foundation Flanders (FWO) and the Agency for Innovation by Science and Technology (IWT), for funding the research conducted in this paper. We also would like to thank the COST-Action TU1303 Novel Structural Skins for the possibility to join WG5 Materials and analysis. As the research is based on the demonstrator of the Contex-T project, we also would like to thank the European Commission for funding the IP-project Textile Architecture – Textile Structures and Buildings of the Future (2006-10).

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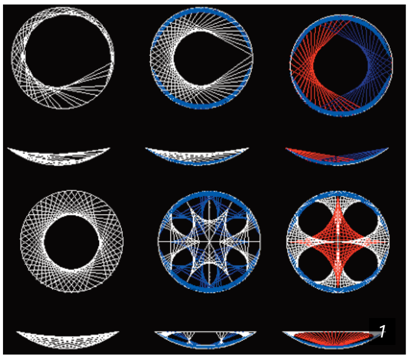
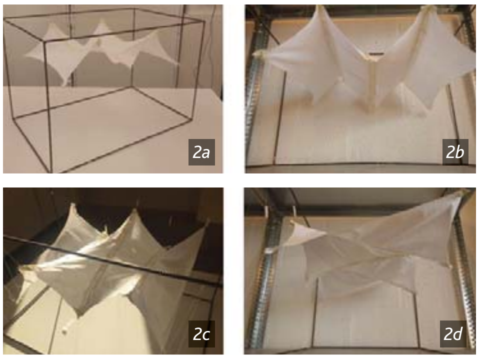
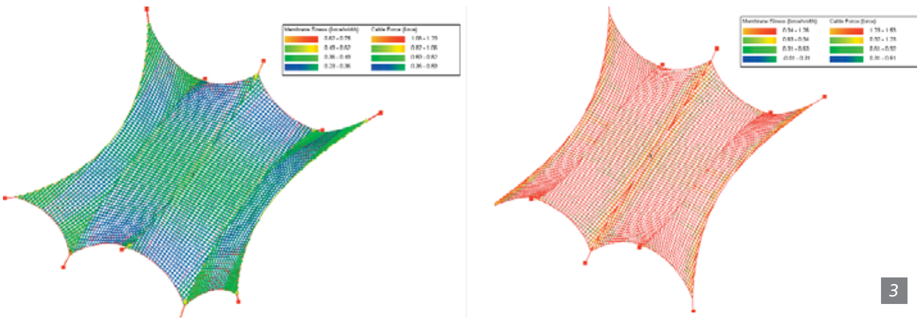
[6] Soft House, IBA, http://www.iba-hamburg/de/
[7] Digital Image Correlation (DIC), http://www.correlatedsolutions.com

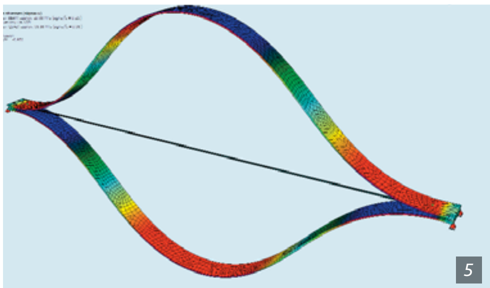
The main objective of the optional course 'Workshop Lightweight Structures' is to design and build a small lightweight structure, based on an advanced concept. The whole process is teamwork based, and involves interacting with experts from practice. Each year a different context is specified.

WORKSHOP LIGHTWEIGHT STRUCTURES 2016-2017 AT VRIJE UNIVERSITEIT BRUSSEL









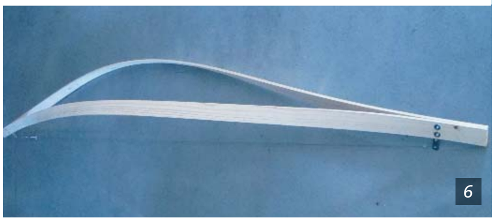


Figure 1. Proposals for Dreamcatcher
Figure 2a-d. Skywaves: verification of the possibility to change the form in a small scale model.
Figure 3. Skywaves: Numerical verification: Left: wave form, Right: anti-symmetric.
Figure 4. Skywaves: Welding of a curved edge.
Figure 5. Leaves: Parametric numerical model: two beams and one cable.
Figure 6. Leaves: Physical model with adjustable connection.
Figure 7. Skywaves: Configuration wave form.
Figure 8. Skywaves: Anti-symmetric configuration.

The task for 2016-2017 was to create an architectural installation that gives an extra dimension to the reception area of Sioen's factory. The point was to showcase the possibilities of textile architecture. Groups of two or three students worked on different proposals. Maxime Durka from Sioen gave feedback and finally three projects were selected to be further developed: **Skywaves, Leaves and Dreamcatcher.**

For Skywaves a scaled prototype was analysed. The concept to be checked was the ability to alter the waveform into an anti-symmetric set-up. It was verified by means of small models (Fig. 2) as well as with numerical simulations (Fig. 3). The change of form is possible if the midline is almost straight.

Once the concept checked, the cutting patterns were generated. Harry Buskes and Steve Aerts from Carpro together with Maxime Durka from Sioen helped the students in the fabrication process: the automatic cutting, the welding (Fig. 4) and the stitching were all explained and done together with professionals.

A parameter study for the out of plane bending of the **Leaves** was performed. It allowed to estimate appropriate sections (Fig. 5).

The final set-up of the prototypes was done the 20th of April 2017. All working models for the design of the Leaves and the Dreamcatcher were shown and discussed. The two alternative configurations for Skywaves were realised.

The variety of required skills throughout the whole design process up to the demonstration is huge, team spirit and sharing responsibilities are a must! The fact of having a drink under the skywaves was rewarding for both students and teachers! We thank Sioen for providing the material and Carpro for the guidance and the fabrication of the membrane.

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