# TensiNews

NEWSLETTER NR. 40
APRIL 2021
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

## WORLD RECORD ON INFLATABLE STRUCTURES FOR HANGARS

RESARCH

## FIRE SAFETY PERFORMANCE OF MEMBRANE STRUCTURES

PROJECTS

## SCENIC FUNNEL-SHAPED SHADING STRUCTURE

## CONTEMPORARY LIGHTWEIGHT STRUCTURE FOR A CASTLE

## SOFT-ROBOTIC COWORKING POD COROLLA

*COVERED COURTYARD OF THE ROMAN HEADQUARTERS OF LUMSA © ANDREA LIVERANI*

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TensiNews INFO

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ISSN 1784-5688

# Edito

*Dear Reader*

*Being a network, we rely very much on meeting each other regularly. The Covid 19 pandemic changed our live dramatically. Instead of physical meetings, we meet now virtual, which makes it easier to meet, but it is of course not the same thing.*

*A year has passed now, since we started with the new TensiNet international non-profit association. Our activities have been concentrated this year in our support for a future Eurocode for membrane structures, and on the topic Sustainability and Comfort.*

*This 40th issue of TensiNews brings a variety of interesting articles. Recent projects from all over the world are presented. A tensile structure in Luxemburg, an Amphitheatre in Turkey, a canopy in the UK, a shading roof over a courtyard in Italy and a walkway covering in Australia. Two temporary or demountable structures, a mobile theatre for a roadshow through the USA and an inflatable hangar for Saudi Arabia. Research results are presented, a bending active pavilion with knitted fabric, and a design study for Dubai Expo. To determine the fire performance of ETFE, a test protocol is proposed, and the environmental performance of ETFE has been analysed in a PhD study.*

*We have started the organisation of our next TensiNet Symposium, you find herein a first information, and more will follow soon. For this autumn some conferences are scheduled, and we all hope that we might be able to join and find a smooth way back to normality.*

*I hope to meet again soon. Meanwhile enjoy this issue of TensiNews. Stay healthy.*

*Yours sincerely,*
*Bernd Stimpfle*

# Forthcoming Events

**Please verify if events haven't been cancelled or been replaced by a tele-conference due to COVID 19 virus**

**TECHTEXTIL 2021** *Beyond innovation* | *postponed to 21-24/06/2022* | Frankfurt am Main, Germany | **https://techtextil.messefrankfurt.com/frankfurt/en.html**

**Textile Roofs 2020/2021** | *10-12/05/2021* | Berlin, Germany | **www.textile-roofs.com** POSTPONED

**IASS** *Annual Symposium and Spatial Structures Conference 2020/2021 - Inspiring the next generation* | *23-27/8/2021* University of Surrey, Guildford, UK | **https://www.surrey.ac.uk/iass2021**

**STRUCTURAL MEMBRANES 2021** | *13-15/09/2021* | Technical University of Munich, Germany | **https://congress.cimne.com/membranes2021/frontal/default.asp /**

**International Conference on Advanced Building Skins Conference & Expo 2021** | *20-21/10/2021* | Bern, Switzerland | **www.abs.green**

**Aachen-Dresden-Denkendorf** *International Textile Conference 2021* | *9-10/11/2021* | Stuttgart, Germany **https://www.aachen-dresden-denkendorf.de/en/itc/**

# TensiNet Meetings

**1st General Assembly**
**5/5/2021 at 15.00**
The 1st General Assembly of TensiNet will be held online.

## TensiNet sessions at Advanced Building Skins Conference & Expo 2021

TensiNet will be represented at the 16th Advanced Building Skins Conference & Expo with two TensiNet sessions on Membrane Architecture: "**Skins from fabrics and foils**" and "**Building Membrane Cladding Systems**". More information will follow.

# Courses

## IMS BAUHAUS® Degree "Archineer®"

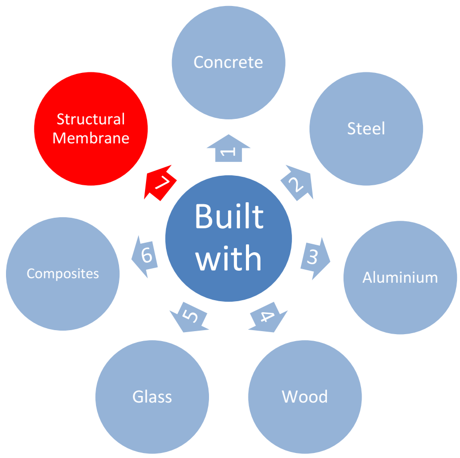
**online course -** All further information about this new programme can be found on the website https://www.ims-institute.org/education-1/archineerr/

# TensiNet Symposium 2023 at Nantes University

*The next TensiNet Symposium 2023 will be organized in collaboration with Nantes University in May or June 2023. The focus will be on* ***Textile architecture: the seventh established building material. Designing reliable and sustainable structures for the urban environment.*** *The 3 main topics are:*

STRUCTURAL MEMBRANE: contemporary, innovative, adaptive daring and impactful solutions

In Jules Verne's hometown, with its focus on innovation and futuristic issues, textile architecture can provide answers to current problems, especially for ever denser cities and for a world that is always on the move.




TENSIONED MEMBRANE STRUCTURES: the seventh building material

Recent advances in the design of membrane structures, development of a Eurocode dedicated to structural membranes: the word membrane must now be part of the daily vocabulary of architects, designers and decision-makers, and the specificities of membrane design must be part of the knowledge of all structural engineers.

STRUCTURAL MEMBRANE: an answer to issues of the 21st century

Lightweight design, well-being, environmental impact, energy and acoustic performance, life cycle of materials and structures, end of life of membrane structures: these keywords are part of the current and future construction challenges and are an important message for the younger generations.

More information will follow in the upcoming months!

Hosting festivities and activities under a contemporary lightweight structure.

# Tensile Membrane Structure for the Koerich Castle

## Luxembourg


*Figure 1. The Koerich Castle, the situation before the intervention in 2018 © Ney & Partners*

*The Koerich Castle, situated along a small stream in the Eisch valley of Luxembourg, is a Medieval vestige rooted in the 12th century and recognized as one of the seven monumental castles in the valley (Fig. 1). The Luxembourgish government, the current owner of the castle, initiated a conservation intervention, which also creates new cultural spaces that make use of the old castle.*
*One of the new features of the castle is the capacity for hosting various festivities and activities (such as shows and concerts) on the elevated platform in the old corps-de-logis. The dimensions of this space are approximately 31m by 10m, with a total surface of 306m². The inner space is enclosed by three facades of 13m height, including the south face which forms a spectacular backdrop when seen from the inner court. Ney & Partners was asked to propose a design for a canopy covering the stage, which would enable hosting events while protecting it from the weather conditions. The design with a tensile membrane structure was chosen after different design variants were presented to the client.*

## Design

Thick masonry walls of the existing east, west and south façades allow the integration of a lightweight structure tensioned in the air between these walls. A primary cable is installed atop the east and the west façades and laid along the axis of the corps-de-logis. The membrane is hung from the two high points on the primary cable and stretched across by the edge cables along the lower perimeter of the structure. The edge cables, anchored on multiple perimeter points on the masonry walls, provide the necessary prestresses to the entire membrane surface.

Starting from the geometric configuration in the preliminary sketch (Fig. 2), six lower points are extended outwards to positions that are 80cm from the interior surface of the wall, in order to maximise the covered area. Two lower points facing the inner court are supported by two columns made of tubular steel profiles with a diameter of 168mm and a height of 7m, which sit on a rocker bearing of 60mm diameter.

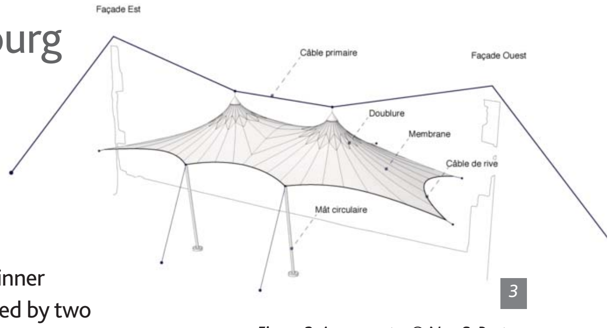



*Figure 3. Axonometry © Ney & Partners*

Requiring no structural support on the platform allows the event organisers to flexibly program the layout for various purposes. The chosen geometry, with a surface area of 240m², defines two equivalent spaces that can either be organized into an audience space and a performance space, or can be entirely dedicated to the stage space. From the viewpoint of architectural integration, the advantage of this solution is its lightness. Not only is the structure support-free and lightweight in the physical sense, it also showcases the character of time in a contemporary language. The visual appearance of the structure demonstrates an excellent integration, maximising the playful contrast between the massiveness of the ancient masonry works with its strictly defined geometry and the lightness of the membrane with a more natural fluid form (Fig. 3).

## Detailing

Water is drained at all eight perimeter points. A rise of 100mm along the edge of the membrane, realised by inserting circular foam profiles, guides the water on the membrane surface to the downspouts. Stainless steel downspout pipes collect water at six points along the interior face of the wall. At two points facing the inner court, water is drained through the supporting masts. These masts are not only used as structural support for the membrane and the drainage of rainwater, but also used to illuminate the stage area (Fig. 4). Several lights are installed at the column head. Other lighting points, independent from the roof structure, are also used to complete the stage lighting.

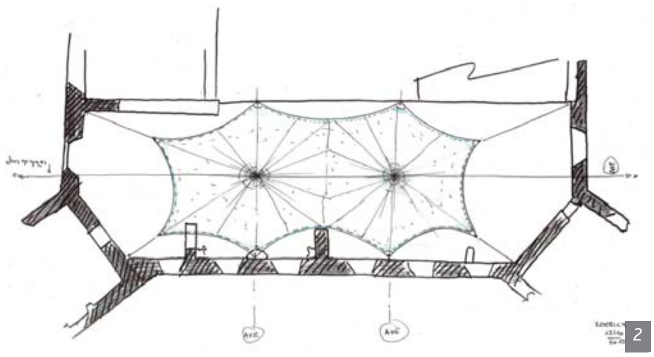



*Figure 2. Sketch in the preliminary design illustrating the membrane and its fixation in the existing corps-de-logis © Ney & Partners*

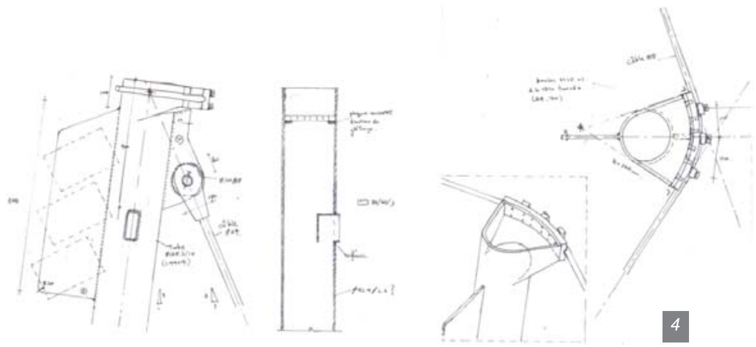



*Figure 4. Detail of the mast head © Ney & Partners*

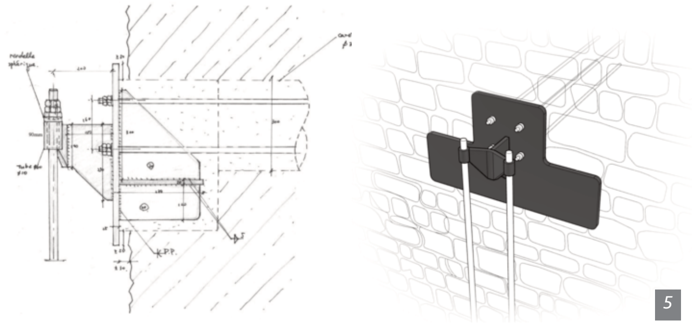


*Figure 5. Anchor detail on the exterior side of the façade © Ney & Partners*

## Pretension

To pretension the membrane surface between the facades of the castle, several reinforcements were required for the masonry wall. Two beams are installed atop the east and west façades, taking up the reaction force from the primary cable and diffusing it along the masonry wall. The anchors on six lower positions in the perimeter (Fig. 5) penetrate the façade and direct the forces towards the micro-pile foundations on the exterior side of the façade.

The nature of such a structure requires a uniform and controlled prestress in the membrane surface. Fork details with length adjustment are installed at several fixation points, which enables the adjustment of the prestress forces in the cables and consequently in the tensile membrane during the execution. Finite element analysis showed the significant concentration of stresses around the two high points compared to the rest of the surface (Fig. 6). In order to address these stresses, reinforcement layers (made of the same fabric as the rest of the canopy structure) are welded onto the primary layer. The radial geometric patterns of the two reinforcement zones provide a play of shadows and perspectives orbiting around the two critical points of the membrane.

*Figure 6. Finite element model © Ney & Partners*

## Material

Special attention is paid to the material choice. Durable materials are used for the membrane fabric and the supporting steel elements. The membrane consists of PTFE fabric with fluor coating. This fabric is highly chemically resistant and has an excellent surface quality, with light translucency of 20%. Because of the exposition to the climatic conditions, almost all the steel elements are made of high-quality stainless steel. Two types of finishes are applied on stainless steel: black paint (the same colour as used for the rest of the new intervention by Fabeck Architect) is applied to the elements that connect to the existing construction. Bead-blasting finishes are applied to the stainless-steel elements that are part of the membrane structure.

## Structural design

Two main challenges were identified for the structural design of the tensile structure, namely the definition of geometry and prestresses, and the introduction of reactions to the substructures.

## Membrane design

The membrane geometry and prestresses are designed in accordance with the French recommendation "*Recommandations pour la conception des ouvrages permanents de couverture textile*". The most critical design parameter was the choice of the prestress forces in the membrane surface: on the one hand, sufficient prestress forces must be introduced in order to achieve high geometric stiffness and prevent large deflections under wind and snow loads. The French recommendation specifies that inversion of the surface curvature due to snow loads should be avoided in order to prevent so-called "ponding", a harmful phenomenon that tensile structures are often sensitive to.

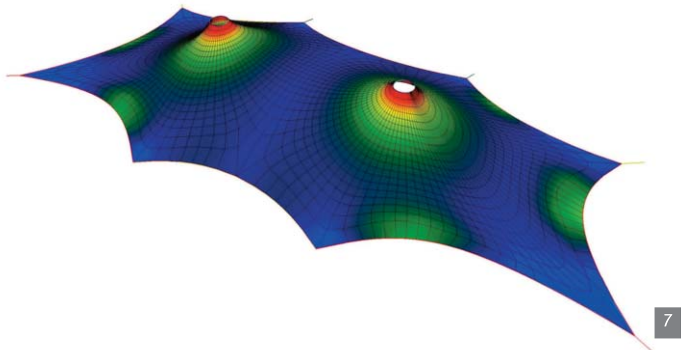


*Figure 7. Stress concentration in the conical shape due to prestressing © Ney & Partners*

On the other hand, the prestresses needed to be kept sufficiently small for two reasons. First, the stresses must be verified for the tensile resistance of the chosen material. In this project, the chosen material is PTFE fabric with a characteristic strength of 80N/mm. This stress limit is particularly important when designing conical surfaces. In such surfaces, the cone centre forms a singular point, towards which stresses drastically increase. For the Koerich castle, the global shape of the membrane can be approximated with two adjacent conical surfaces lifted by two points, which join meet at the centre (Fig. 7). In order to lessen the effect of stress concentration, the central opening at the two points is made sufficiently large, approximately 80cm in diameter, and furthermore up to two layers of reinforcement are added to the principal layer (Fig. 8).
The second motivation to limit the prestress forces are the reaction forces. Since the membrane structure is anchored in the existing castle ruins, the total reactions must be kept in control. Therefore, the contribution of the prestress to the reaction was also kept sufficiently small.
Based on the criteria described above, the amount of design prestresses was defined. The form-finding resulted in the average prestresses of approximately 4kN/m in warp direction and 2kN/m in weft direction. The prestresses in the perimeter cables vary between 15kN and 30kN. For the determination of an approximate global geometry, form-finding was carried out using Rhino and Grasshopper with the physics engine Kangaroo in the preliminary design phase. The finite element software package Sofistik was used for the final form-finding and structural analysis in the detailed design phase.

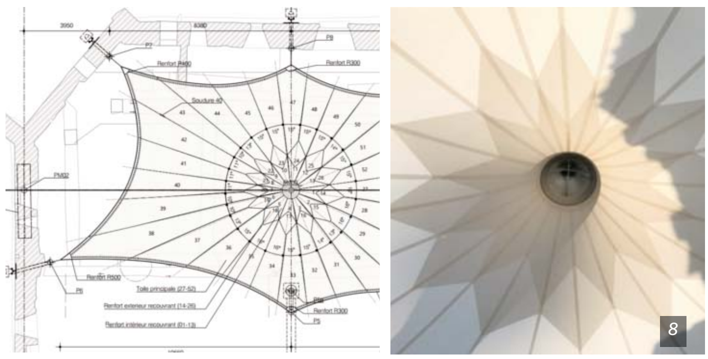


*Figure 8. Cutting pattern and reinforcement layers © Ney & Partners*

## Anchor design

A challenge in the structural design was the load transfer from the tensile structure to the substructures. The central idea in the design is to use the existing structures as load-bearing elements that take up the loads from the membrane. However, the initial study indicated that the existing masonry wall is not sufficiently strong to resist the horizontal reaction from the membrane structure (Fig. 9, left). Therefore vertical bars in the exterior of the wall were conceived, which can orient the reaction vertically, in such a way that the reaction resultants remain within the masonry volume (Fig. 9, right). The anchor detail at the opposite side of the wall are designed in conjunction with these bars. The anchors are constructed out of steel plates and filled with concrete (Fig. 5).

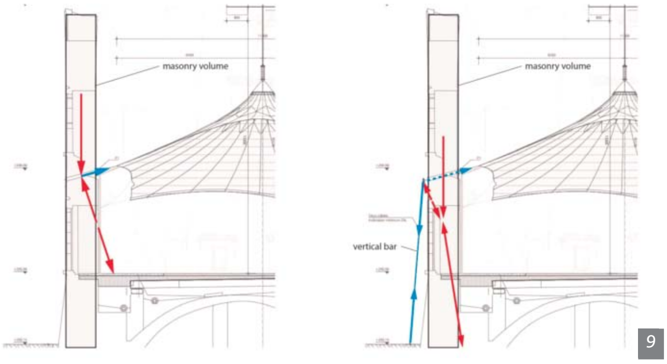
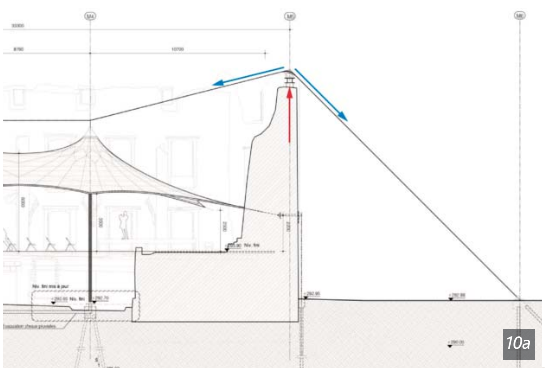



*Figure 9. Strut-and-tie model of the reaction introduction: without reinforcement (left) and with external bars (right) © Ney & Partners*

Another important detail is the connection of the principal cable to the top of the walls. If the steel detail was rigidly anchored in the masonry wall, it could induce an unfavourable parasitic horizontal component in the reaction. In order to guarantee that only vertical reactions are transferred, a custom sliding bearing is integrated in the base of the deviation detail, which allows approximately ± 10cm of horizontal displacement in case of temperature dilatation and external loads (Fig. 10).


*Figure 11. The monumental Koerich Castle with its contemporary lightweight structure © Ney & Partners*

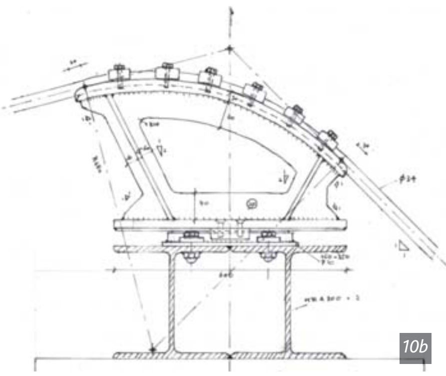




*Figure 10a-b. Wall top deviation detail for the principal cable with sliding bearing.© Ney & Partners*


*Figure 12a-b. Impression of the realised structure © JL Deru*

The Koerich Castle project demonstrates an exemplary use of tensile structures which, responding to the client's demand, enhances the historical monument into a contemporary cultural space. The tensile structure is successfully realised with attention to detail and in harmony with the castle ruins (Figs. 11-12).

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Said Sahmaoui
Eric Bodarwé
Laurent Ney
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https://ney.partners/

| | |
|---|---|
| Name of the project: | Koerich Castle – New Cultural Space |
| Location address: | Rue du Château, 8385 Koerich, Luxembourg |
| Client (investor): | Ministry of the Culture Service des sites et monuments nationaux, the Luxembourg government |
| Function of building: | cultural heritage, public event venue |
| Type of application of the membrane: | roofing for an outdoor event venue |
| Year of construction: | 2019 |
| Architects: | Ney & Partners (membrane roof), Fabeck Architects (renovation and public space) |
| Multi-disciplinary engineering: | SGI Consulting s.a. (renovation and rehabilitation of the castle) |
| Structural engineers: | Ney & Partners (membrane structure) |
| Contractor for the membrane (Tensile membrane contractor): | Schreiber s.a. |
| Supplier of the membrane material: | Sefar AG |
| Manufacture and installation: | Schreiber s.a. |
| Material: | PTFE coated PTFE fabric (SEFAR® Architecture TENARA®) |
| Covered surface (roofed area): | 310m$^2$ |

# Hasan Kalyoncu University Amphitheatre

Gaziantep, Turkey

## An oyster-like acoustic double layered membrane covering.


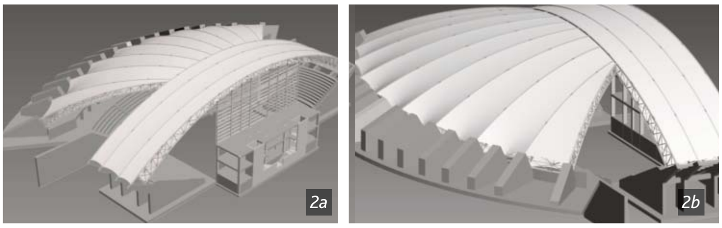


*Figure 1a/b. Bird view of the oyster-like membrane covering of the Hasan Kalyoncu University Amphitheatre*
*Figure 2a/b. 3D modelling of the new amphitheatre*
*Figure 3a/b/c. The double layered canopy covering approx. 5000m² with a capacity up to 3000 spectators*
*© Asma Germe*

*The Amphitheater of Hasan Kalyoncu University is located in South East Region in Turkey. The location of the structure is known with its heavy snow which affects the design of the system structurally. The structure serves as a social activity and exhibition center of the university. This makes 'the acoustics' as one of the important design criteria. The host city, Gaziantep, is famous with its history and cuisine. The original name of the city is 'Antep' who played a very big role for the independence fight after the first world war. Hence, to honor the city, the title 'Gazi' which means 'Veteran', is given.*
*The structural morphology is generally based on the 5-storey reinforced concrete structures in the city itself, except the historical areas which are conserved until today. That's why, the amphitheater has become a Landmark which is assertive in her own right comparing with the plan area.*

### Project

Hasan Kalyoncu University Amphitheater was initially designed as the conventional covering system consisting of the solid cladding panels supported by structural steel trusses. Asma Germe (AG) changed the cladding system with the tensioned fabric cover and revised the steel trusses accordingly. By doing so, the amount of the steel has decreased nearly 20%. This was a huge advantage and one of the main reasons to change the system. Other important reasons were the esthetic and the construction time which only took 3 months from design to completion of the structural system (Figs 1-2).
The acoustic issues are addressed by using an inner secondary membrane which has been developed by Serge Ferrari named 'Alphalia Silent Aw'. Some other solid additional panels were placed over the stage for better performance. The outer membrane is from Serge Ferrari Flexlight Advanced 1302S2.

The total covered area is approximately 5000m$^2$. The main arch truss is spanning 105m and its height is 17m. The secondary arches are spanning around 42m. The capacity of the amphitheater is 3000 people. The roof cover is designed as an oyster shape according to the customer's request. The oyster form helped to drift of the snow which is a dominant load factor for the region.

The covering system consists of two layers. The outer layer is tensioned between the top cords of the trusses. The inner layer is tensioned between the bottom cords of the trusses. The facades of the double layer steel trusses are covered by membrane to sustain UV protection for the inner membrane. This is also needed for the back facades of the trusses to prevent the snow accumulation over the inner membrane since the lower layer of the truss stands on the ground there.
With the spacious atmosphere sustained by the structural design, the led lightening along the trusses, and the up and down movable stage the amphitheater became the host of the great shows (Fig. 3).

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| | |
|---|---|
| Name of the project: | HKU Amphitheatre |
| Location address: | Gaziantep/ Turkey |
| Client (investor): | Hasan Kalyoncu University |
| Function of building: | Exhibition Center |
| Type of application of the membrane: | PVC membrane and Acoustic membrane |
| Year of construction: | 2019 |
| Architects: | Kübra Kalyoncu |
| Structural engineers: | Dr. Meltem Şahin & Çağlar Samat |
| Consulting engineer for the membrane: | Dr. Fevzi Dansık |
| Main contractor: | Kalyon Construction |
| Contractor for the membrane (Tensile membrane contractor): | AG (Asma Germe) |
| Supplier of the membrane material: | Serge Ferrari |
| Manufacture and installation: | AG (Asma Germe) |
| Material: | Serge Ferrari Alphalia Silent Aw (inner membrane), Serge Ferrari Flexlight Advanced 1302S2 (outer membrane). |
| Covered surface (roofed area): | approximately 5000m$^2$ |

# LUNAR DOME SPACE THEATRE

## A large-scale mobile tent construction for the Apollo 11 roadshow in the USA

*In 1969, Apollo 11 took the first humans to the moon – an event that moved the world. On the occasion of its 50th anniversary, a roadshow has been planned through several cities in the USA, enabling visitors to relive the milestones of the spectacular moon landing via a three-dimensional video show at first hand. The venue is provided by a mobile theatre tent, conceived by Matthew Churchill and designed by architect Teresa Hoskyns, which already creates an impressive appearance from the outside. With its considerable size, accommodating 1.600 visitors, the Lunar Dome was conceived as a temporary structure. One particular feature of this lightweight tent structure with its membrane skin is the fact that all its individual elements which are optimised for quick assembly and easy transport. This applies both to the outer skin and to the three-dimensional 360-degree projection dome inside the Lunar Dome. The supporting steel structure, the substructure, outer skin and projection surface along with the ETFE foyer façade for the mobile theatre were developed by consulting engineers formTL from Radolfzell.*

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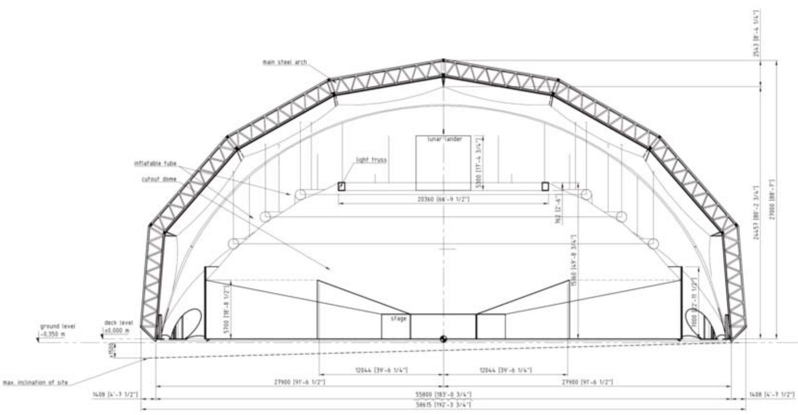
*Figure 1. Interior view showing the video projection dome forming a protected and experiential space © Jim Cox Photography, Matthew Churchill Production Ltd*
*Figure 2a-b. Section and roof plan indicating the main arch supports of the theatre tent © formTL*
*Figure 3. Cranes are used for the erection of the main arches assembled with plug-in connectors while lying on the ground © Matthew Churchill Production Ltd*

### Tent roof under arch supports

Four steel trussed arches form the supporting structure for the impressive structure of the Lunar Dome. The greatest load of the 73m long theatre tent is borne by both main arches, which are arranged in the central area, symmetrically inclined and visible from the outside. These have an impressive span of 55.8m and at their highest point they tower up to 27m above the ground. At the front and rear side of the Lunar Dome above the foyer and backstage area are located two more approximately 11m high trussed arches. All four arches consist of rectangular framework elements connected together with bolts. Steel cables link the whole structure in order to keep the arches in position (Fig. 2).

The base points of the arch frames are pin connected to the steel base plates that are anchored into the ground with large pegs and serve as a foundation. The formTL engineers paid great attention to ease of assembly in their plans: The individual segments of the arch supports can therefore be composed with plug-in connectors while lying on the ground. They are then erected with cranes, positioned over the foundation plates, fastened to the foundations with bolts and finally locked with steel cables (Fig. 3).



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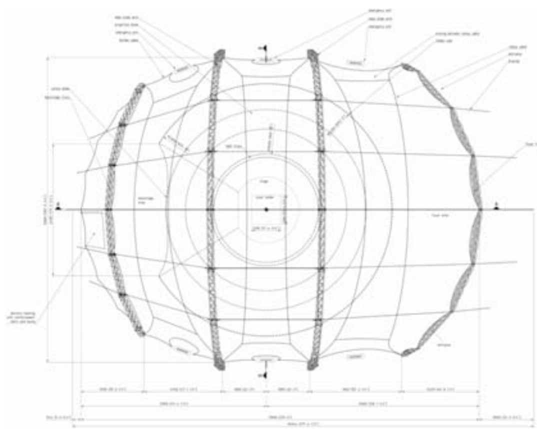

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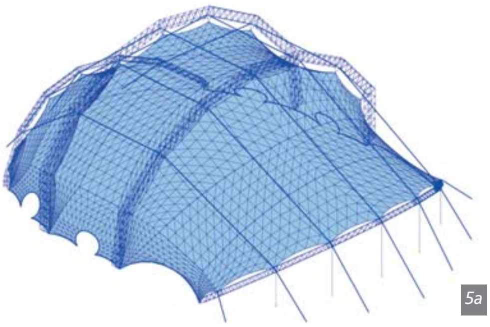

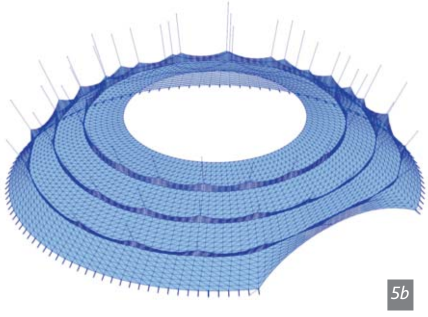

## Skin

The skin of the impressive tent roof consists of a PVC-coated polyester fabric approximately 4.900m² in surface area. It is coated white on the outside and black on the inside. In order to transfer the load of the enveloping surface to the structure, steel ridge cables are integrated into the membrane beneath the arched support structure. Realised as double cables, they simultaneously serve as a field joint. While translucent ETFE cushions close off the foyer to the outside (Fig. 4) – front wall supports up to 10m height beneath the trussed arch bear the cushion facade – the membrane above the backstage area provides tension on the opposite side. It is anchored to the ground at its base points with pegs.

The projection dome in the interior, with a diameter of 46m and 15m in height likewise offers an impressive spatial sensation for visitors. It consists of a sound-absorbing PVC-coated polyester membrane that was also optimised for easy set-up. A large-format cut-out towards the backstage area allows a clear view to the screen located behind it (Ground Control) (Fig. 5). For assembly, the first stage involves the individual panels being connected on the ground with shackles, then electric winches integrated into the arch supports pull the mem-brane upwards on so-called boomerang mountings. They are attached to the ridge cables of the membrane. When the membrane dome has reached its final position, the mountings are bolted onto the cross struts of the trussed girders. The membrane is then tensioned onto the arch bases where it is attached.

The lightweight concept thought through in detail by formTL ideally meets the requirements for the Lunar Dome: The video projection dome forms a protected space where visitors are carried quietly back to the time of the first moon landing; in addition, the light con-struction made from a supporting steel structure and a membrane skin enables the flexibility needed, so that the Apollo 11 roadshow can be moved quickly and easily!

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| | |
|---|---|
| Project: | Apollo Theater, Apollo Production Concepts US Tour 2019 |
| Client: | Matthew Churchill Production Ltd |
| Function of building: | mobil theatre |
| Year of construction: | 2019 |
| Architect: | Teresa Hoskyns and Matthew Churchill |
| Structural planning, membrane planning: | formTL ingenieure für tragwerk und leichtbau gmbh, Radolfzell/DE |
| Producer: | Matthew Churchill Production Ltd. and Nick Grace Management Ltd, UK |
| Architecture: | Teresa Hoskyns |
| Engineering: | formTL ingenieure für tragwerk und leichtbau GmbH, Radolfzell, Germany |
| Engineer of Record: | Wiss, Janney, Elstner Associates, Inc. Northbrook, USA |
| Steel contractors: | Boon Chang Structure Pte Ltd, Singapore, CORBO Engineering, Inc., Caraquet, Canada, Anceschi Alberto e Paolo srl, Rio Saliceto, Italy |
| Contractor for the membrane: | Canobbio Textile Engineering, Castelnuovo Scrivia, Italy |
| Membrane material supplier: | Verseidag-Indutex, Krefeld, Germany, SergeFerrari, La Tour di Pin, France |
| Ropes: | FAS SpA, Cinisello Balsamo, Italien |

*Figure 4. Translucent ETFE cushions closing off the foyer to the outside © Matthew Churchill Production Ltd*
*Figure 5a-b. 3D modelling showing the outer membrane with the main arches and the secondary structures (a) and the projection dome with its suspension system (b) © formTL*
*Figure 6. Impressive temporary structure during day and night © Matthew Churchill Production Ltd*

# Buildair H75-SAEI Hangar

## Jeddah, Saudi Arabia

## World record on Inflatable structures for hangars

*In July 2019, the largest inflatable hangar of the world has been installed by Buildair in Jeddah. Its main function is to shelter and maintain aircrafts such as Airbus 330 or Boeing 777-200ER, during an expected lifetime of 7 years. In addition to its size (97,9x90x33m), other outstanding values are:*

- *structural efficiency: 40.000kp/8.811m$^2$=4,5kp/m$^2$*
- *storage volume of parts (700m$^3$) = 3‰ of the built volume (228.365m$^3$)*
- *total time (including design, manufacture, transport and installation): 6 months*

*These values are much lower than those of a conventional hangar.*

### Antecedents

The idea of using air pressure to support buildings originated from F.W. Lanchester in 1918 (T. Herzog, 1976). The succession of inflated tubes forming a barrel vault has been used for field hospitals (Fig. 1). A prominent application was the FUJI Pavilion at the Osaka Expo'70 (Fig. 2) and the closest antecedent is the H54 Hangar for Airbus, Getafe Air Base, Madrid (Fig. 3).

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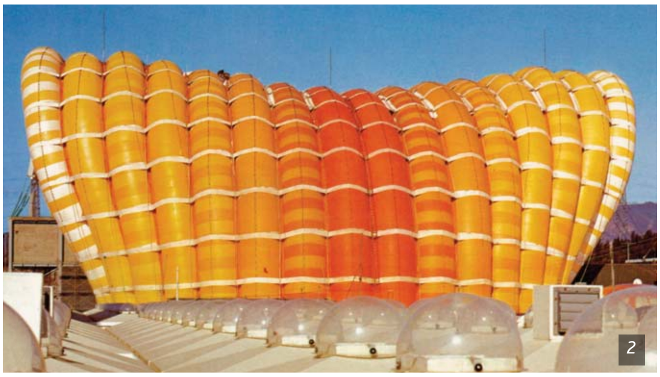

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### General description

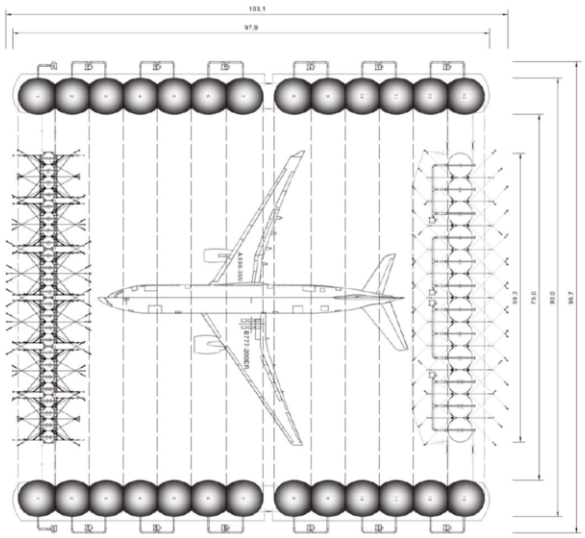
At first glance, the most striking thing about the hangar is its overall dimension: 97,9m in length, 90m in width (corresponding to 75m of free interior span) and 33m outer height corresponding to 25,5m of free vertical interior height (Figs. 4-7). The main body is based on a succession of 13 inflated tubes that are reinforced by belts and anchored to the base slab. It is complemented by two inflated vertical enclosures at both ends. Note that the tubular arches are pressurized but the utilisation space is not. There is no pressure difference inside/outside and therefore special airtight gates are not necessary.

The tubes of the main body are Ø 7,5m in diameter and curved, forming a 90x33m semi-elliptical outer profile (Fig. 6). They are inflated at a low pressure of 20mbar, that could be increased to 25mbar in case of peak wind loads. The internal pressure provides shear and bending rigidity to hold the loads acting over the structure and minimize deformations.

The inflated tubes are bounded by a net of belts as a cage to limit the deformations and to transmit the internal forces to the anchoring points. Three different types of belts have been designed depending on the structural behavior and internal forces expected (Fig. 8):
1) spines and ribs following the direction of the tubes. They bear the bending forces and reduce the deformation in this direction.
2) braces around the tubes keep their cohesion and bear the circumferential component of the stress and deformations in the membrane mainly produced by the internal pressure.
3) radial belts and crosses placed between tubes increase the stiffness in this plane, which is very relevant for the wind lateral load.
All the belts are connected to each other to configure a tensioned network in such a way that forces are transmitted axially to the anchorage points avoiding bending and compression.

The main body includes an additional membrane surrounding the whole set of tubes conceived as a protector layer against the sun radiation and waterproof to ensure the requirements related to water leaks or air entrance through the interphase between the tubes (Fig. 9).

*Figure 1. Transportable Medical Units of the US Army (T. Herzog, 1976).*
*Figure 2. Y. Murata & M. Kawaguchi, 1970: FUJI Pavilion, Osaka.*
*Figure 3. Buildair, 2015: H54 Hangar for Airbus, Getafe Air Base, Madrid.*
*Figure 4. The H75-SAEI hangar, Jeddah.*



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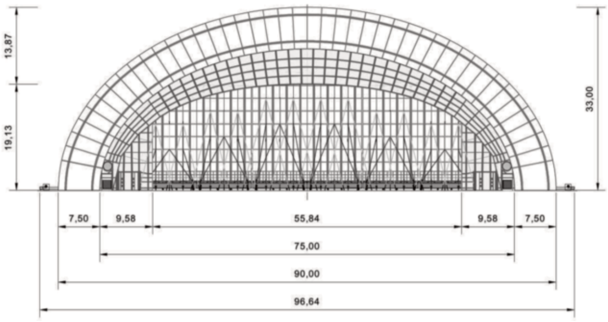


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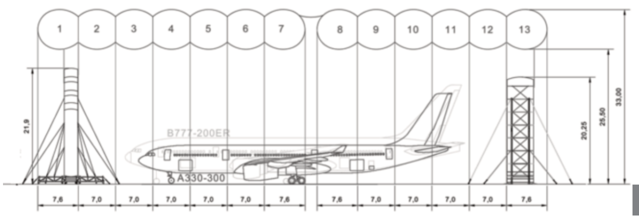


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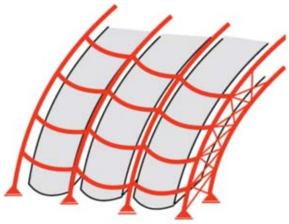

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*Figure 5. Plan. Note that due to safety requirements a 2,3m gap is left between tube 7 and 8.*
*Figure 6. Front view. The tubes are curved forming a semi-ellipse.*
*Figure 7. Longitudinal section.*
*Figure 8. Belt network.*
*Figure 9. Additional membrane for waterproofing and protection.*
*Figure 10. Visualisation of the open-close operation of the front enclosure.*
*Figure 11. Carriages of the front enclosure under construction.*
*Figure 12. Front and top views and section of the front enclosure.*
*Figure 13. Connection detail. Anchor of belts to the slab.*

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## Enclosures

The front enclosure is the entry and exit door of the aircraft. It relies on air-inflated to 30mb internal pressure to bear the external actions. They are surrounded by belts, hold by vertical beams and placed on steel carriages that move (Figs. 10-11). Every carriage is 10m wide and the top surface is raised 1m above the ground. The tubes have a diameter of 2,257m while their height is variable from 12,5m to 20,5m because the geometry of the enclosure follows the semi-elliptic shape of the hangar (Fig. 12). A set of supporting cables is built at both sides of the enclosure in order to increase its stability.

The back enclosure is non-movable and relies also on air-inflated vertical tubes, 5,1m in diameter and a variable height from 14,87m to 19,75m according to the shape of the enclosure. They are inflated to 30mbar of internal pressure and, together with their surrounding belts, they are supported by vertical beams anchored directly to the ground.

## Anchors

The hangar is anchored to a reinforced concrete slab (93,7m wide and 106,08m long) using different types of anchors according to the structural elements and loads. The belts are anchored by means of special steel plates provided with one or more passing bolts (Fig. 13). The membranes of the tubes and the emergency exit are anchored using eyebolts.

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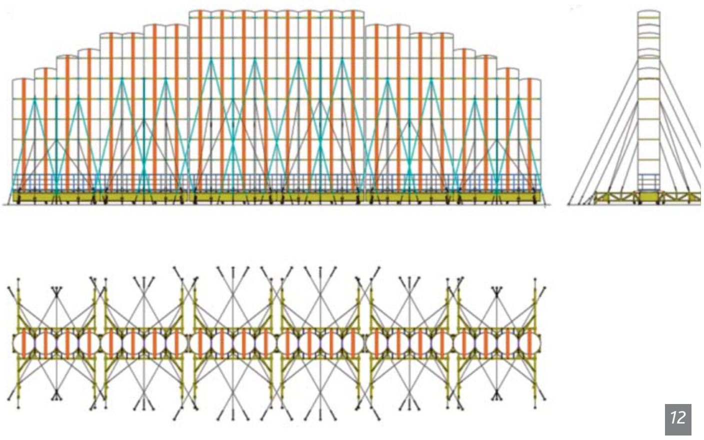

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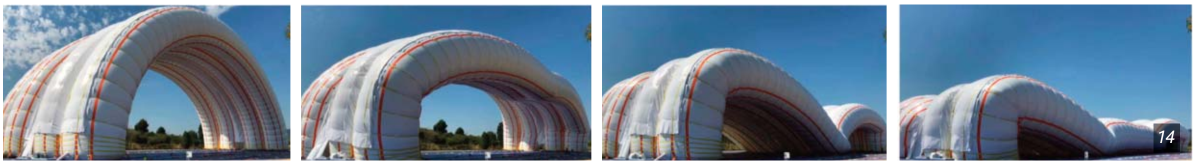

## Manufacture

The Buildair manufacturing team has worked 24 hours a day (3 shifts) to fulfil the strict deadlines of this project, stitching and welding 43.872m$^2$ of membrane and 36.861,50m of belts. Buildair not only manufactured the hangar but also designed, installed and controlled it. This is a relevant aspect of the project, carried out by a single company avoiding subcontractors that lengthen the term, embroil the management and increase the cost. As a quality test, four tubes were installed in Barcelona in March 2019 during the design and manufacturing phase (Fig. 14 and https://youtu.be/1axt-u3hD-4, visited 24/01/2021)

## Transportation

The whole structure was shipped to Jeddah by sea in 24 containers of standard 40-feet size. Tubes, waterproof layer, curtains and belts occupied 10 containers, the metallic parts for enclosures and anchorages required another 7, and blowers, services and the fire fighting system needed the remaining 7 containers.
Note that the final total volume enclosed by the textile parts of the hangar is 228.365m$^3$. They have been transported in 10 standard 40-feet containers that enclose a usable volume of 700m$^3$. That is, the stored volume is only 3 ‰ of the hangar actual volume when installed. Therefore, the storage volume of the parts is 652 times lower than the volume built. This key aspect allows the large-scale inflatable hangars to be manufactured in Barcelona and shipped anywhere in the world with very low costs. In addition, everything could be easily dismantled and transferred to another nearby or remote location.

## Installation

The hangar was built on site in June and July, 2019 by a team of 16 people (Fig. 15). All the set-up before inflation took a month and the inflation of the main body has been performed on June 26th. Operations were carried out in Jeddah in summer, with temperatures up to 43ºC. So, the hangar was built in night shifts to minimize the exposure to the sun and high temperatures (Fig. 16). At the end of July 2019, the enclosures have been set-up in about two weeks, while the services (lighting, climate control, fire protection) and maintenance staff offices were finished in a month. The total design and construction term took 6 months which can be considered unrivalled for an inflatable hangar of this size. It should be noted that the aircraft maintenance hangar is considered an equipment that does not require a building permit.

## Operation

The inflated tubes of the hangar are steadily fed by a blower system to ensure the stability of the structure even in case of failure of one engine. The main body has fourteen blowers, so every pair of tubes has one main blower and a secondary blower in case of failure. The blowing system in the main body is complemented by an automatic control system to manage the internal pressure of the tubes in relation to external actions over the hangar. The front enclosure has one blower for each carriage while four blowers are enough for the back enclosure. Special mention should be made of the control and monitoring system which allows the hangar to be managed remotely from a mobile or PC (Fig. 17).

*Figure 14. Deflation test showing initial state and after 15, 28 and 60min.*
*Figure 15. Inflation of the hangar.*
*Figure 16. Installation of the hangar at night.*
*Figure 17. Remote control (wind speed, internal pressure, temperature, blower operation, etc).*

## Cost

In the total cost of the project is included the cost of the inflatable structure, the cost of the services within the hangar and the cost of the slab. The investment has been low compared to that required by a conventional steel structure.

## Conclusion

The design, manufacturing and implementation of the largest inflatable hangar in the world has been possible making the most of membranes and belts as parts of an inflated network, that optimizes their capacity avoiding inconvenient solutions (under bending or compression) as much as possible.


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|---|---|
| Name of the project: | Hangar H75 - SAEI |
| Location address: | Jeddah Airport Base, Kingdom of Saudi Arabia |
| Client (investor): | Saudi Aerospace Engineering Industries - SAEI (KSA) (https://www.saei.aero/Pages/Home.aspx) |
| Function of building: | Hangar to host an Airbus 330 or a Boeing 777-200ER |
| Type of application of the membrane: | Pneu |
| Year of construction: | 2019 |
| Designer, structural and consulting engineer for the membrane, engineering of the controlling mechanism, main contractor and contractor for the membrane: | BuildAir Engineering & Architecture (https://buildair.com/) |
| Supplier of the membrane material: | SIOEN (https://sioen.com/en) |
| Covered surface (roofed area): | 8.811m$^2$ |
| Membrane: | 43.872m$^2$ PVC coated polyester fabric with surface treatment SIOEN TT0117E (650g/m$^2$) |
| Polyester straps: | 36.861,50m |
| Steel slings: | 3.744,80m |
| Blower engines: | 24 |


Bibliography :
https://buildair.com/hangar-h75-jeddah/ (visited 24/01/2020)
J.M. González, J. Marcipar, C. Estruch, E. Cuartero & E. Oñate, 2019: "Numerical simulation of an inflated structure for an aircraft hangar", Proceedings of the IASS Annual Symposium and Structural Membranes, Barcelona.
T. Herzog, 1976: "Pneumatische Konstruktionen", Verlag Gerd Hatje, Stuttgart.

SATTLER PRO-TEX GMBH

*Architen Landrell were approached by Pritchard Architecture on a nationally significant project to relocate the last remaining Landing Craft Tank (LCT) from the D-Day landings to the D-Day Museum, Southsea. After the original single ply roof with a timber soffit proved too expensive, the design team came to talk to Architen Landrell about designing a tensile fabric canopy to go over the ship, supported by a large, curved, cantilevered steel structure.*


Southsea, UK

# Landing Craft Tank (LCT) Canopy at the D-Day Museum

## Design

Key to the design intent was a slender, curved leading edge, flush white underside and grey top side. Architen Landrell worked with all the key stake holders including the National Museum of the Royal Navy and local authority to meet these design demands (Fig. 1).

The desired clean lines were achieved by locating the tensile fabric membrane on the underside of the steelwork. This hid all of the structure above but posed a challenge for the drainage of rainwater. Our specialist tensile fabric design and engineering team developed a clever hopper detail around the posts to drain water effectively and ensure no leaks (Figs. 2-3).

## Material

PVC coated polyester was an obvious choice due to the fact that it is available in a range of colours, offers a long lifespan, easy maintenance and also met the client's tight budget. Further discussions determined that a blackout fabric would be preferable thus allowing the opportunity to project film or light on to the canopy in the future. Due to the strict planning restraints Architen Landrell had to find a blackout fabric with white underside and a specific grey upper which led them to SATTLER's POLYPLAN Tent Manege 671 Dual Colour Type II.

- Block-out: light-blocking layer in the membrane's core allows to darken a room and a multi-coloured design of the tent roof
- Duo-coating: outside and inside of the membrane can have different colours
- Available as type I, II or III
- Flame-retardant: compliance with current safety standards


Markus Derler
markus.derler@sattler.com
https://protex.sattler.com/en/fabric-selector


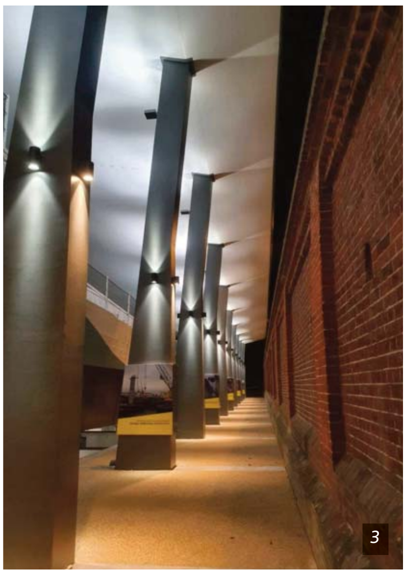

*Figure 1a-b. Night and day view of the membrane covering the Landing Craft Tank*
*Figure 2. Construction detail with the membrane underneath the steelwork*
*Figure 3. Impressive colonnade with the "hanging" membrane*
*© Peter Langdown*

| | |
|---|---|
| Name of the project: | Landing Craft Tank (LCT) Canopy |
| Location address: | The D-Day Story, Clarence Esplanade, Southsea, Portsmouth, Hampshire, PO5 3NT (www.theddaystory.com) |
| Client (investor): | National Museum of the Royal Navy, The D-Day Story with backing from the National Lottery Heritage Fund |
| Function of building: | Protective cantilevered canopy over the LCT |
| Type of application of the membrane: | A tensile fabric canopy supported by a large, curved, cantilevered steel structure |
| Year of construction: | 2020 |
| Architects: | Pritchard Architecture |
| Structural engineers: | Mann Williams |
| Consulting engineer for the membrane: | Artura Design and Engineering Ltd |
| Main contractor: | Ascia Construction Ltd |
| Contractor for the membrane (Tensile membrane contractor): | Architen Landrell Manufacturing Ltd |
| Supplier of the membrane material: | Sattler PRO-TEX GmbH |
| Manufacture and installation: | Architen Landrell Manufacturing Ltd |
| Material: | Polyplan Tent Manege 671 Dual Colour Type II from SATTLER PRO-TEX |
| Covered surface (roofed area): | 970m$^2$ |

# BeTA PAVILION

## CNC Knitted Textile Performance for a Bending-Active Biotensegrity Assembly

***Background for the project***

*BeTA Pavilion (Fig. 1), a Bending-Active Biotensegrity Textile Assembly, is an installation developed by a team of designers, researchers, and students from Kent State University for the 2019 International Association for Shell and Spatial Structures (IASS) Form & Force Expo, organized by Working Group 21: Advanced Manufacturing and Materials. The pavilion tested the dynamic formal opportunities of biotensegrity logics through a material assembly composed of elastically bent glass fiber reinforced plastic (GFRP) and Computer Numerical Control (CNC) knitted textiles. Inspired by animal vertebrae typologies, the structure was assembled with a set of 45 pre-stressed and self-stabilized tetrahedron modules arrayed to achieve structural equilibrium with a range of dynamic motion. The global geometry of the 2mx2mx1.6m form-active structure was developed to respond to local changes in external forces carried by a network of bespoke CNC knitted fabric pieces. The adaptive structure reacts to human touch through kinetic movement while remaining structural stable and retaining efficient curvature and form. This article is developed based on a previous paper by the authors (Davis-Sikora et al, 2020), but with discussions highlighting the performance of CNC knitted textiles.*

### Design concept

Many novel structural forms with complex curved geometries are derived through experimentations in form and force equilibria. Form-finding methods championed by such figures as Antoni Gaudi, Heinz Isler and Frei Otto leveraged material testing to visualize physical laws that led to new paradigms of structural thinking for complex force distribution systems (Boller and Schwartz, 2020). As a network of precisely balanced components, tensegrity structures rely on form-finding methods to accurately predict states of self-equilibrium across a range of topological conditions. First built by Kenneth Snelson, with the term coined by Buckmininster Fuller, tensegrity structures are composed of isolated compression members braced by a continuous tensioning network.

They are considered a highly efficient resilient system due to their high strength-to-weight ratios, stability and efficacy with minimal structural elements.

Their rapid deployability and controlled pre-tensioning ('tunability') offers a robust typology that has been adopted by a variety of disciplinary fields from biology to cellular mechanics. Tensegrity logics have launched new paradigms of understanding in biomechanical movement and kinematic "living" structures with a capacity of shape adaptability.

The BeTA pavilion installation adopts the logics of functional anatomy and self-organization fundamental to biotensegrity principles based on Kenneth Snelson's and Buckminster Fuller's tensegrity paradigm. Conceived by Dr. Stephen M Levin M.D. in the 1970s, biotensegrity describes an organizing, biological principle of locomotion characterized by a complex interconnected network of tension and compression elements arranged to resist physical forces.

Biotensegrity systems are dynamic and lightweight structures that formally adapt to achieve continued states of equilibrium. Shape adjusting features were instrumental to the BeTA pavilion design. A bending-active system was adopted for the installation to showcase the pavilion's biotensegrity assembly as a passively stable structure. The pairing of bending-active GFRP rods modules with tensioned CNC knitted textile connections produced a reverberant structure when touched.

Forty-five elastically bent regular tetrahedral modules with ten distinct sizes were scaled and sequentially arranged in one chain to describe a hyperbolic paraboloid geometry for the pavilion. Each self-similar tetrahedron module was connected to its adjoining neighbor by an accompanying CNC custom knitted textile. The initial geometry of the pavilion was developed computationally using Rhino/Grasshopper/Kangaroo²®, and its structural performance verified through the continual interplay between physical and computational form-finding. Rhino/Grasshopper/Kiwi!3D interface enabled the integration of isogeometric finite element analysis into a computer aided design

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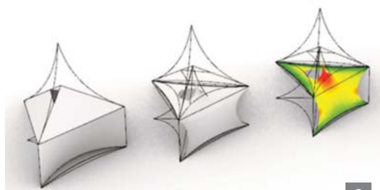

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*Figure 1. BeTA Pavilion*
*Figure 2. Computational Form-finding using Kiwi!3D*

environment to 'visualize' the stress distributions in the textiles (Fig. 2) (Kiendl, 2010; Breitenberger, 2016; Bauer, et al, 2017; Davis-Sikora et al, 2020). This process pinpointed the highest stress distribution at the top vertex of the bottom tetrahedron, and a relatively high tensile stress distribution in the middle portion of the fabric, as well as a high tensile stress distribution around the opening. Default material values of GFRP rods and ethylene tetrafluoroethylene as membrane were used to create the digital model, and to find the deformed geometry of the proposed form-active hybrid system. Actual material performance data (i.e., modulus of elasticity, tensile strength, and stress-strain curve for non-linear analysis) could be used to more accurately simulate the force-form relationships of the proposed design.

Large GFRP tetrahedrons arranged at the bottom of the pavilion were each fabricated with six single rods measuring 46cm to 76cm in length, and 0.3175cm in diameter. Three rods were connected at each corner vertex by a 3D printed plastic connector to produce a tetrahedron shape. Flexible GFRP rods with a diameter of 0.1575cm, and a length between 30.5cm and 38cm were used to construct smaller modules with the desired curvature and shape. To accommodate the reduced stiffness, three rods were bundled together and secured at their vertices and mid-points using the connectors shown in Figure 3.

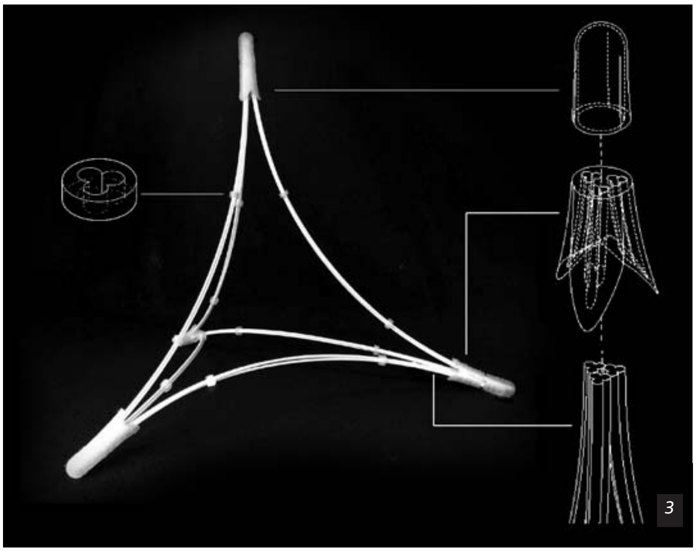
CNC knitted textiles were pretensioned to link the 45 bending-active tetrahedron modules into a continuous chain. Tensioning for each textile was then later adjusted to achieve the pavilion's target geometry. The textile design and patterning were crucial to the project's structural performance and dynamic motion.

## CNC KNITTED TEXTILE

The textile serves as the "soft tissue". It carries tension, connects each tetrahedron 'vertebrae', and makes it possible to form a chain like that of the human spine. Each textile piece incorporated: 1) four fabric pockets, 2) three bottom ribbed tubes, and 3) three knitted bands to connect each tetrahedron with its adjacent neighbors. The knitting pattern shown in Figure 4 was programmed using M1PLUS® software[1]. The platform provides a variety of ready-to-use Knit and Wear modules, as well as flexible programming to adjust and optimize knitting patterns according to customized specifications. All textiles were knitted using polyester air covered spandex yarn on a Stoll CMS 530 HP, 7.2-gauge industrial knitting machine (Fig. 5). The knitting pattern file was developed as a 14-gauge knit with seven fields of intarsia knitting, which used 10 yarn carriers with two ends of air covered spandex consisting of 20 denier spandex core with one ply of 150 denier textured polyester.

Knitting details are illustrated in Figure 6. A total of five different knit structures were designed on each piece of textile. Twenty-two different sizes of textiles were knitted, ranging from 160 stitches wide x 282 stitches long to 284 stitches wide x 752 stitches long, to connect ten different tetrahedron sizes.

An interlock stitch (1) was used to create a strong fabric with knitted slits, through which adjacent bands were looped into a chain. Since a high tension was to be carried by the fabric (2), a tubular pointelle (a double-layered knit), was selected for the main portion of the textile. Four open-ended tubular sections (3) were designed at the bottom of the piece to sleeve GFRP rods through and connect the tetrahedron edge to the textile. The 4 tube design provided options for variable lengths to adjust the tension placed on the fabric. Pockets (4) and (5) were knitted with an interlock jersey structure to provide additional strength at the three tetrahedrons end point connections. The stretched textile, in Figure 7, indicates the high-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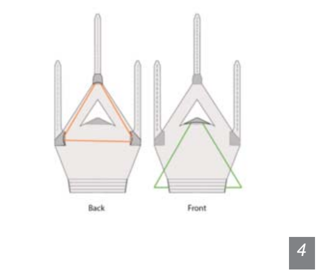

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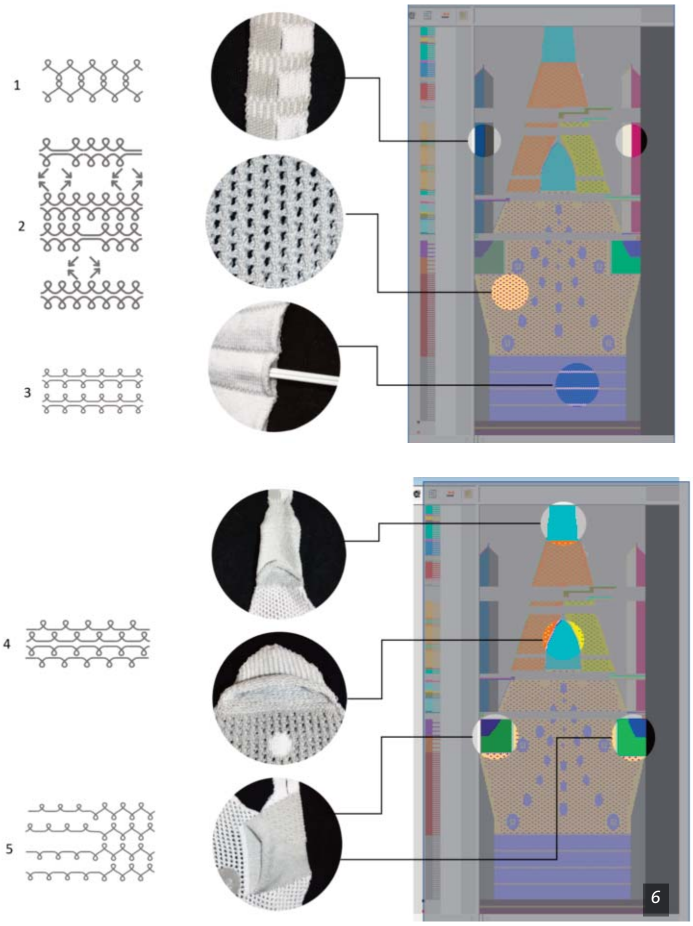

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*Figure 3. 3D Printed Connectors at the Vertex Connors of Small Tetrahedron*
*Figure 4. Textile Knitting Pattern*
*Figure 5. Stoll CMS 530 HP knitting machine*
*Figure 6. Details of Knitting*

[1] www.stoll.com/M1PLUS

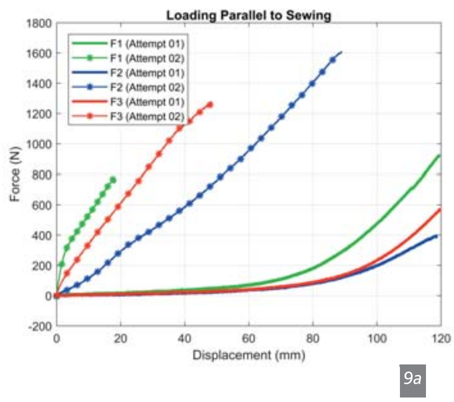
est tensile stress at the vertices. The interlock jersey structure at the knitted pocket carries sufficient tensile capacity to support the stress concentration at this end point.

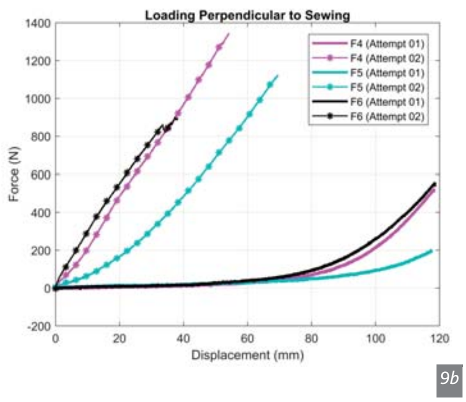
## Structural performance of the CNC Knitted fabric

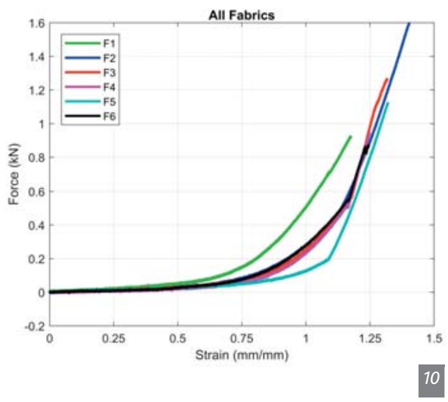
To better understand the structural behavior of the knitted fabric, uniaxial testing with loading parallel and perpendicular to the knitting, respectively, were completed for the CNC knitted textile with a gauge width and length of 10cm. The textile pieces were placed in an MTS universal servohydraulic testing machine equipped with a load cell and data acquisition system (Fig. 8). A total of six pieces were tested with three (F1, F2, and F3) loaded in the direction parallel to the knitting, and three (F4, F5, and F6) loaded in the direction perpendicular to the knitting. The load versus machine stroke results are shown in Figure 9. For each sample two tests were performed. The attempt 1 loading for each textile was to stretch the piece with an elongation of 12cm, which corresponds to the maximum displacement (stroke) of the machine head. After unloading, the piece was released from the jaws of the machine head, and the cross-head was moved upward. The same piece was gripped again by the jaws and the position of the machine head adjusted to consider the permanent deformation of the fabric after the first attempt. The new initial length was recorded for each sample. Pieces were loaded in tension again in attempt 2 until tensile rupture occurred as shown in Figure 8 (b). The testing data was recorded for both attempts for each piece, as shown in Figure 9. The ultimate capacity of each sample is defined as the addition of tensions applied in the two attempts. Samples F1, F2, and F3 had an ultimate load capacity in the range of 1,700N and 2,000N, and a maximum elongation in the second attempt between 2 and 8 cm. The other three had an ultimate load capacity in the direction perpendicular to the knitting ranging between 1,400N and 1,900N, and an ultimate


*Figure 7. Stretched Textile*
*Figure 8. Tensile Testing for the double-layered textile*
*/a. Tensile Testing*
*/b. Rupture of the Textile*
*Figure 9 a/b. Force versus machine stroke for each attempt of the tensile tests*
*Figure 10. Force versus strain responses*





elongation in the range of 4cm and 7cm in the second attempt. The preliminary testing indicates the CNC knitted textiles exhibited similar structural performances in both directions. The preliminary testing results in attempt 1 loading indicate nonlinear inelastic behavior of the textile under a low level of forces, which suggests that the textile is very stretchy, (i.e., the textile filaments tend to stretch while losing the original weaved shape), and the deformation of the textile is not linearly proportional to the tension applied. In addition, large residual stretches were observed after unloading at the end of the fist loading attempt. This phenomenon may be due to the combination of the material and knitting pattern. The polyester spandex yarn may be still in the elastic range under the loading, however slippage of the yarn in the knitted fabric occurred during the loading to generate the residual deformation due to tension. Preliminary testing results indicate the textile exhibited similar mechanical performances in the direction either parallel or perpendicular to the knitting. Additional systematic investigations are required to understand the relationship between material, knitting pattern and mechanical properties. This information would then be used for a more accurate computational form-finding to predict geometric deformations of the stretched textile.

Textile strain was determined by dividing the machine stroke by the initial length between the gripping jaws for each attempt. The strain was then used to combine the response of the two attempts as shown in Figure 10. The two curves from the same sample were combined by overlapping the portion of the two responses for which the load range was the same. It can be noted that when attempts were combined, the force versus strain responses for textiles tested in both directions were consistent. Two branches can be identified. The first branch exhibits a nonlinear trend corresponding to the stretching of the textile. The second branch, most likely, corresponds to the full mechanical engagement of the fibers in tension. The slope of the second branch is consistent among all samples, which suggests that the modulus of elasticity in the two directions is very similar.

As shown in Figure 2, the tensile stress distribution in the textile is not uniform, which was reflected in Figure 7 with large openings or holes in the areas with higher stress and strain. With residual deformation under the low level of stress, the stretch in the CNC knitted fabric still exhibited a linear but non-elastic behavior with the higher level of tensile force applied as shown in Figure 9. The level of tension in the textile not only influences the overall geometry of the pavilion, but also affects the stiffness of the structure. Higher tension generates a stiffer structure with a higher frequency of vibration. Because of the lightweight nature of the assembly, textiles for the bottom tetrahedrons required higher tension (and stiffness) to erect the form-active, hybrid structure.

## Conclusion and future research

The construction of an adaptive, hybrid biotensegrity structure, is the first step in an ongoing probe into the complex dynamics of compliant form-active systems. The CNC knitted textile exhibited revealing structural behaviors under the uniaxial loading conditions including non-linear behavior and residual deformation under the low stress levels, and linear but non-elastic behaviors under the high stress conditions. The structural behaviors are similar in the directions parallel and perpendicular to the knit.

BeTA pavilion was assembled multiple times with the same materials. Because of the residual deformation in the textiles under a low level of stress, the global geometry of each assembly appeared different. Slight variations in localized tensioning during each process of assembly produced morphological variations of the target shape. A 'smart' system could be integrated in future projects to monitor strain levels in the knitted fabric; access creep behavior under a long-term loading on the textile; and confirm deviations from the intended shape. Future applications would also benefit from an integrated assessment of elasticity and tension levels produced through the paired performance of GFRP rods and CNC knit fabric. The knit textile embodies a range of performative attributes that drive tensile capacities including yarn type, knit structure, and CNC knit processes (i.e., yarn ends per inch, the tension with which the yarn was knitted, and textile direction in relation to stretch). Moving forward, additional physical and computational modeling of scaled, CNC textile samples targeting selected performance criteria will enable extended testing for long-term and multiple installation efforts.

## Acknowledgements

The authors would like to acknowledge the financial support provided by the University Research Council, College of Architecture and Environmental Design, and School of Fashion at Kent State University. Our thanks are also given to TechSyleLAB at Kent State, InnovaKnits North Carolina, and Structure/Material Testing lab at the Case Western Reserve University for equipment/facility support, and the following students from Kent State University, who participated in the fabrication of BeTA Pavilion: Fred Wolfe, Haley DeRose, and Maame Amoah.

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Italy and UAE

AN INNOVATIVE SOFT-ROBOTIC SKIN ABLE TO ADAPT TO CHANGING OUTDOOR CONDITIONS, CREATING A HYBRID BETWEEN INDOOR AND OUTDOOR

*Figure 1a-b. Corolla in open and semi-open configurations*

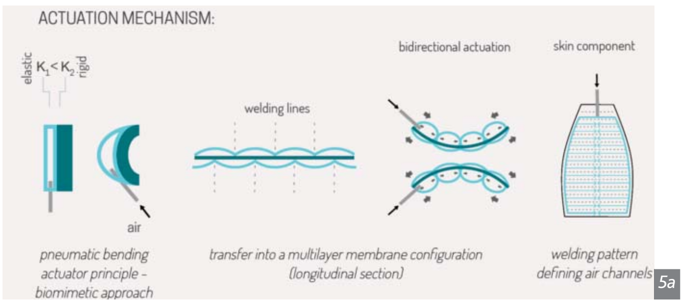
# Soft-robotic coworking pod Corolla

*This prototype is the outcome of a research project into soft-robotic responsive envelope systems, aimed to create a new, lightweight, adaptive envelope typology to provide increased comfort and an energetically efficient solution for outdoor living. Soft robotics is an emerging field in robotics that takes inspiration from invertebrates which are able to move without any rigid body parts. Emulating those biological mechanisms provides significant advantages over traditional rigid robotics, such as reduced weight, cost and increased robustness and flexibility. Corolla is one of the winning entries of the 'Design Competition Expo Dubai 2020', an initiative promoted by Regione Lombardia and Camera di Commercio di Milano Monza Brianza Lodi in collaboration with Politecnico di Milano, under the theme "Connecting Spaces". The winning projects were exhibited at the HOMI Outdoors Fair in Rho Fiera Milano and will be showcased in several public events in 2021, including Milano Design Week and Expo Dubai 2021 (Fig. 1).*

## Project

The co-working pod consists of a modular steel structure which is enclosed by a soft-robotic skin system made of eight pneumatic actuators manufactured with TPU coated Nylon fabric, 349cm long and 64cm and 144.5cm wide at their ends when deflated (Figs. 2-4). Each of these 'petals' is made of two internal air chamber networks, stamped with a special welding pattern, consisting of a series of horizontal welding lines. The distance between the lines has been designed according to the geometry and resistance required, and it is directly related to the maximum curling angle and overall ability to resist gravity and external forces such as wind. Adequate spaces are kept from the edges allowing the circulation of the air in between the chambers. This specific pattern is designed to make the petal curl up or down when the chambers are inflated (Figs. 5-6) at different pressures.
The actuators are fixed to the structure using eight folded steel supports which are radially fixed with hinges to the top octagonal frame of the pod, supported by a curved beam cantilevered from the steel basement. A pneumatic system connects two air pumps located in the base with each side of the eight actuators, enabling the control of all bottom or top sides of actuators. The column base is strategically positioned on the perimeter of the space, freeing up internal space for collaborative interactions between the users. The pavilion is also equipped with an electric circuit which provides the power distribution to the LED lights and the connection between the sensors, the data logger and the controlling system. A tensioned TPU coated Nylon fabric cover gives the column and tables their curvy look.

According to the concept, the system is fully automated and its response is controlled by a microcontroller connected to the weather sensors, valves and air-pumps. In this way, on a nice sunny day, the petals are left open to enjoy the natural airflow while providing shade from the sun. In case of a rainy, cold or extremely hot day, the skin system closes to protect users from the elements providing a thermally insulated space which can be climatically controlled for optimal comfort of the users (Figs 7-8). The pod is also designed to be equipped with a compact HVAC system for heating and cooling, Wi-Fi, charging spots and a PV solar panel to reduce energy grid dependency (Fig. 9).



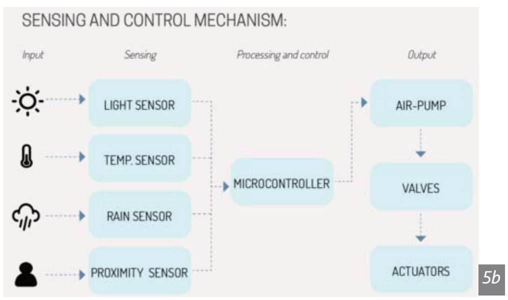
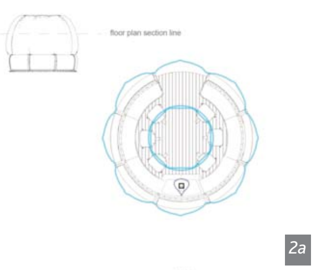
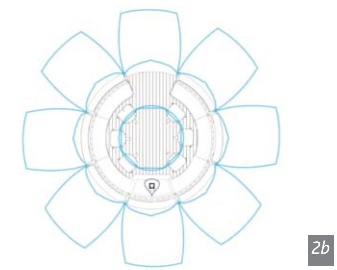
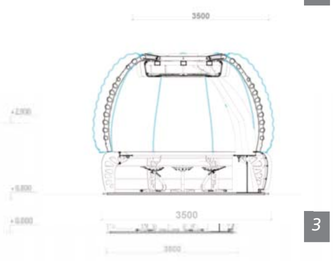



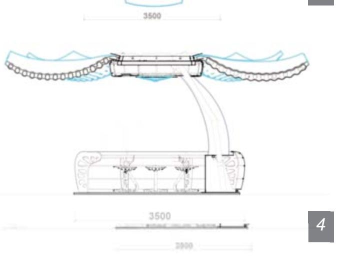

*Figure 2a/b. Floor plan configurations*
*Figure 3. Section A-A'*
*Figure 4. Section B-B'*

*Figure 5a/b. Actualisation mechanism*
*Figure 6a/b. Test component curvature*

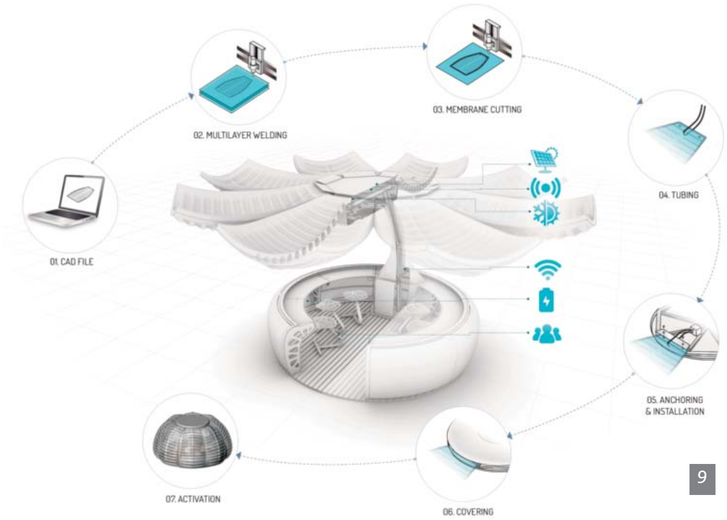







## Further opportunities and realisations

This innovative prototype aims to investigate the potential of the use of automation in architecture as well as providing a better understanding of cost-effective pneumatic actuators made of coated fabrics. Such light-weight kinetic systems that use no rigid parts and are activated by air alone are demonstrated to be feasible by this project on a larger scale than previously attempted, on a building scale. By exploiting the flexible, shape-shifting attributes of soft-robotic actuators it is possible to devise highly versatile envelope systems that can accommodate for different needs or conditions, such as the shift from an open cover to an enclosed space in Corolla. This ability together with weather sensors provides the opportunity to fully automate this adaptive process in an effective and resource-efficient way, much like a living organism.



*Figure 7. Corolla in closed configuration*
*Figure 8. Corolla interior view with the petals semi-open*
*Figure 9. Actuator component fabrication*

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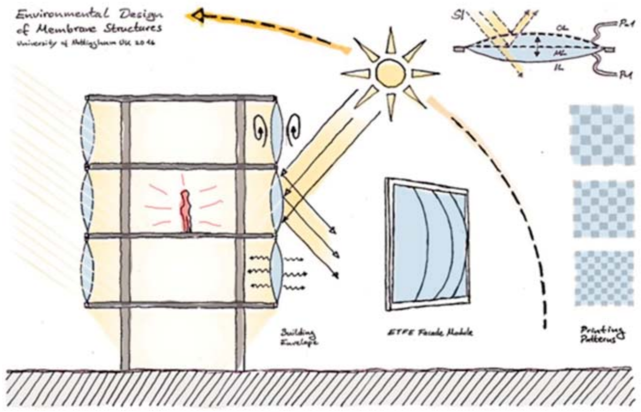
| | |
|---|---|
| Name of the project: | Corolla |
| Location address: | Temporary Pavilion installed in Milan (Italy) and Dubai (UAE) |
| Client (investor): | Design Competition Expo Dubai 2020 |
| Function of building: | Open-air coworking space |
| Type of application of the membrane: | Envelope system |
| Year of construction: | 2019 |
| Architects: | Ofir Albag & Martin Huba (Studio albaghuba), Omer Alraee |
| Multi-disciplinary engineering: | Paolo Beccarelli, Maco Technology srl |
| Structural engineers: | Paolo Beccarelli, Maco Technology srl |
| Consulting engineer for the membrane: | Paolo Beccarelli, Maco Technology srl |
| Engineering of the controlling mechanism: | Maco Technology srl |
| Main contractor: | Maco Technology srl |
| Contractor for the membrane (Tensile membrane contractor): | Maco Technology srl |
| Supplier of the membrane material: | Rivertex UK Ltd |
| Manufacture and installation: | Maco Technology srl |
| Material: | Riverseal® 202 (Thermoplastic Polyurethane coated Nylon fabric) and steel |
| Covered surface (roofed area): | 9.77m² (closed configuration) |



# SWITCHABLE ETFE FAÇADES

## Environmental performance of climate adaptive building envelopes




The development of transparent, light, flexible, and resistant materials like ethylene tetrafluoroethylene (ETFE) foil allows rethinking the function of the building envelope as an interactive and moderating membrane between the internal and external environment. Air inflated ETFE foil constructions, forming pneumatic cushions, are structurally efficient and have increasingly been used in state-of-the-art architecture. However, the prediction of the thermo-optical behaviour of ETFE structures in building façades is a challenge for designers and manufacturers. The proposal of adaptive or switchable systems, which can be modified on demand to respond to changing climate conditions, is a recent technological answer to that challenge. Nevertheless, the understanding of the impact of switchable ETFE façades on the energy and daylighting performance of buildings, as well as on comfort and user experience, is still limited and represents a barrier to large scale implementation.

In a PhD research campaign, carried out at the University of Nottingham by Jan-Frederik Flor under the supervision of Prof. Yupeng Wu, Dr. Paolo Beccarelli, Prof. John Chilton and Dr. Yanyi Sun, switchable multi-layer ETFE cushions were investigated through a series of studies, using ray-tracing, energy simulations and virtual reality, to assess daylighting qualities, energy performance and view perception of spaces enclosed with switchable ETFE façades. The main findings of the conducted studies revealed the superior energy and daylighting performance of spaces enclosed by switchable ETFE cushions. In comparison to static ETFE cushions and standard double glazing, climate adaptive switchable systems actively reduce solar gains and improve the environmental performance of the building envelope. Implications on energy consumption and natural daylighting of the enclosed spaces are of relevance for future applications in building façades: Glare reductions of 59% and an increase of useful daylight illuminance of 58%, with annual energy savings of up to 56% were predicted. However, the study also found that view clarity of foils, print inks, and patterns of current switchable ETFE cushions is not yet satisfactory and remains a challenge for future esearch and development.

It is hoped that the outcomes of this research campaign will contribute to advancements in ETFE-foil façade technology, that may lead to energy savings in the building sector and support the agenda against climate change. For more information on the project and downloading relevant literature, visit https://janfrederikflor.wixsite.com/home

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# FIRE SAFETY PERFORMANCE OF MEMBRANE STRUCTURES

## ETFE in particular

*In any subject area related to the provision of safety, failure is typically the most effective mechanism for evoking rapid reform and an introspective assessment of the accepted operating methods and standards within a professional body (1). When it comes to fire safety, lessons can be learned from the reaction of the cladding system - the roof and/or the façade – in case of a fire inside the building.*

*A good example has been a fire at Condor Campus, the headquarter of Condor at Frankfurt International Airport in western Germany, in 2016. The Headquarter was opened in March 2013 and is certified as a LEED Gold project. On December 29, 2016, a flight simulator had caught fire in the Condor office building at Frankfurt airport. The simulator, much of which burned out, contained a replica passenger cabin. Some 200 people were forced to evacuate the office building. Fire fighters were alarmed at 11:52. They managed to extinguish the flames within 45 minutes. At 12:30 the fire was extinguished. At 13:20 it was announced that the whole building was smoke-free and that the employees were allowed to return to their workplaces. Due to the fact, that the roof of the hall of the flight simulator was cladded by an ETFE foil system heat and smoke were released immediately after the foils were melted and therefore the roof was entirely open towards the outside. ETFE foil claddings just retract to the extrusions when temperatures exceed 200°C. Thus, the fire fighters had direct access to the source of fire. The primary steel supporting structure was kept in place. Additionally, there was no risk of parts falling down from the roof.*

### The classification systems for building products

This specific response of a membrane cladding system is not taken into account by actual classification systems. Only the reaction to fire of the building cladding material is analysed, neither the building cladding system nor whole the building structure. Today, typical parameters are fire resistance and flammability. In particular, the national standards like DIN 4102 *Fire behaviour of building materials and building components* (2), BS 476 *Fire tests on building materials and structures* (3), NFPA 701 *Fire tests for flame propagation of textiles and films* (2019) (4), or ASTM E 84 *Standard Test Method for Surface Burning Characteristics of Building Materials* (2020) (5), focus on the material performance. Consequently, the European classification system EN 13501 *Fire classification of construction products and building elements* (6) categorises the fire performance according to the fire performance of a specific building product. Each product is tested according to the procedures given in EN 13823 *Reaction to fire tests for building products* (7), and EN ISO 11925-2 *Reaction to fire tests - Ignitability of products subjected to direct impingement of flame* (8). The test results in accordance with EN 13 823, clause 9, provide good evidence of the contribution of the building material under investigation regarding fire growth (FIGRA – fire growth rate), smoke growth (SMOGRA – smoke growth rate), and flaming droplets/particles. The reaction-to-fire test according to EN ISO 11925-2 provides good evidence regarding the ignitability of the building material. For membranes, the ignitability is analysed for both surface exposure and edge exposure. Additionally, the ignition of filter paper placed below the test sample indicates, whether potentially burning droplets might cause ignition of the filter paper.

The classification is carried out in accordance with clause 11.6 of EN 13 501-1:2010 (6). Without going too much into details, the norm differs between five classes A, B, C, D and F regarding flammability and ignitability. Products classified A2, B, C, D obtain an additional classification s1, s2, and s3 regarding the smoke production and an additional classification of d0, d1 or d2 regarding the production of flaming droplets and/or particles. Just as an example, ETFE (ethylene tetrafluoroethylen) foils are classified as B-s1-d0 (9).

However, the background information concerning the reaction to fire classification of a product given in Annex A of the EN 13 501-1 (10) states under clause A.2.2, that the validation of the classification of products in terms of their contribution to fire growth and post flashover fires is based on a large scale scenario. As a reference scenario for the definition of class limits the test procedure published in ISO 9705-1:1993 *Fire tests – Full scale room test for surface products* (11). The method does not evaluate the fire resistance of products. Thus, fire classes defined according to EN 13 501-1 cannot be understood without detailed knowledge gained from a full-scale test of whole the cladding system. Up to now, the building industry has set focus on comparison between the fire classes achieved by performance tests of the cladding material only, not on the fire performance of different building cladding systems. For membrane structures, the actual constricted perception does mislead the valuation regarding reaction to fire performance of membrane cladding systems. Unfortunately, the reference standard for a full-scale room test cited in EN 13 501-1 is not suitable for membrane cladding systems. In close cooperation with RISE, the Research Institute of Sweden nearby Gothenburg, Vector Foiltec has identified ISO 13784-1 *Reaction to fire test for sandwich panel building systems – Part1: Small room test* (12) as perfect for a test of the reaction to fire performance of membrane structures, ETFE building cladding structures in particular. The scope of ISO 13 784-1 is a "test for determining the reaction to fire behaviour of sandwich panel building systems, and the resulting flame spread on or within the sandwich panel building construction, when exposed to heat from a simulated internal fire with flames impinging directly on the internal corner of the sandwich panel building construction". According to Per Thureson, fire expert at RISE Research Institute of Sweden, this method is similar to ISO 9705-1, which is a small room scenario of the same size as ISO 13784-1. The main difference is that ISO 9705-1 has a room enclosure in which the product is mounted and in ISO 13784-1, the product itself forms the room scenario without any outer enclosure (13).

## The Small Room Test according to ISO ISO 13784-1

In order to form a basis for a new technical fire classification for membranes, Vector Foiltec has requested a test of a standard ETFE cushion systems at RISE Safety – Fire Research. The test was performed on February 13, 2019. The nominal external dimensions of the test room were 3.7m by 2.5m by 2.5m (length by width by hight). A standard Vector Foiltec Texlon® F16 aluminium frame system was attached to the structural steel framework of the test room in order to hold the ETFE foil cushions. The setup of the foil cushions was a standard 3-layer ETFE foil system comprising an outer foil of 250µm thickness, a middle foil of 100µm, and an inner foil of 250µm. The individual layers were welded together at the edges. They were stabilised to approximately 250Pa by means of a low-pressure air supply system. The outer foil was coated by a dark print pattern that covers 92% of the cushion area with highly pigmented ink (DH 9:92 dark, aluminium pigments).

Smoke gases were vented and air was let into the small room through a door opening. The ignition source was a gas burner, placed close to the left rear corner on the back of the wall. The burner heat output was 100kW for the first 10 minutes and then 300kW for another 10 minutes. The smoke gases coming out through the doorway and through the joints of the sandwich panel system was collected by a hood and exhaust system (in accordance with method 2, clause 9.4.2) from where samples were taken for gas analysis. Heat release and smoke production rate were measured continuously.

The heat from the gas burner in phase 1 (100kW output) caused the foil material of both wall panels next to the flame to melt and form holes. When the heat energy was increased to 300kW after 10 minutes, the foil cushion panel in the roof corner started to melt and form a hole, also (Fig. 1).
Figure 2 shows both the damage of the rear and left wall panels as well as the damage of the roof panel. Two holes of 1.5m² each were formed in the walls and a hole of 0.5m² was formed in the roof corner.



*Figure 1. Flame after increase to 300kW.*
*Figure 2. After the test holes of 1.5m² were formed in the façade foil cushions and a hole of 0.5m² was formed in the upper left corner of the roof cushion.*

The observations are summarised in Table 1.

| TABLE 1: OBSERVATIONS | |
|---|---|
| Ignition of specimen | No |
| Flames emerging through the doorway | No |
| Opening joints and flaming from joints | No |
| Flaming debris/droplets | No* |
| Smoke and flames outside the room through joints | No |
| Flame spread through core of specimens/panels | Yes** |
| Flashover | No |
| Collapse of structure | No |

* *Droplets were not burning.*
** *Some panels were burned through all of the three foil layers.*

Figure 3 shows the heat release rate HRR during the test. No contribution from the cladding system was found. The gas burner was switched off at 20:00 minutes and the test was terminated at 30:00 minutes.

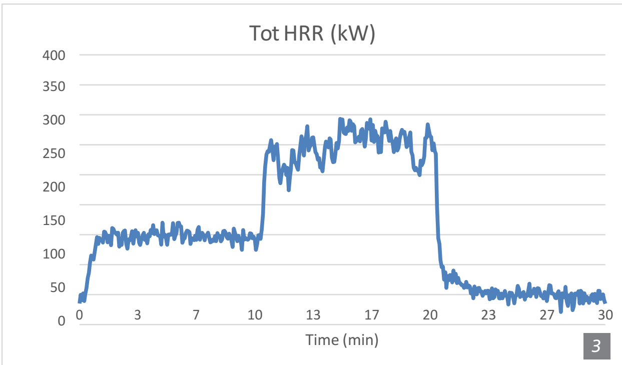


*Figure 3. Heat release rate HRR during test, including burner heat output.*

Figure 4 shows the smoke production rate. After the test the lenses of the smoke measurement system showed some contamination, causing the photometric signal not to return to the baselevel. Therefore, the measured smoke production most likely can be seen as a worst-case performance.

Figure 5 shows the gas temperatures in different height in the centre of the door opening. The height is indicated in table 2.

The heat from the gas burner caused the foil material to melt. There were holes in all three of the foil layers of the ceiling panel and of both wall panels in the corner next to the burner.

The damage was limited to the burner corner. All external wall and ceiling thermocouples were intact in position after the test. All aluminium extrusions as well as the silicone gaskets except those next to the burner in the rear left hand corner did not show any signs of damage.

Calculation of the fire growth rate FIGRA and the smoke growth rate SMOGRA is not part of ISO 13784-1 but is defined in ISO 9705-1. As mentioned before, both tests deal with a small room scenario of the same size and can be considered to be comparable. FIGRA is defined as the peak heat release rate during the test (excluding the burner heat output) divided by the time to reach peak HRR. Since the measured HRR of the cladding product was below the systems detection limit (< 50 kW) FIGRA was set to zero (0 kW/s) (14).

SMOGRA is defined as peak smoke production rate SPR (averaged over 60s) divided by the time to reach peak SPR. If peak SPR is less than 0.3m²/s SMOGRA is set to zero. For the tested products (transparent and printed) SMOGRA can be calculated as given in Table 3:

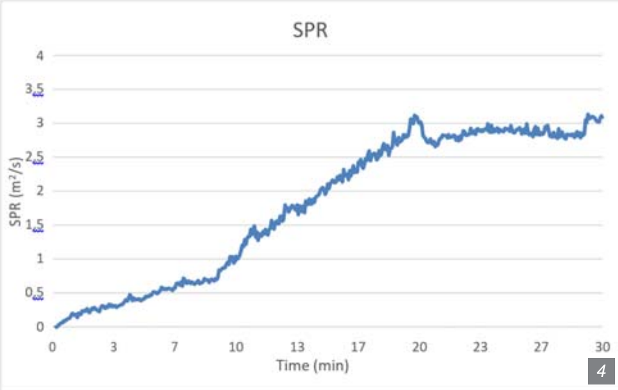


*Figure 4. Smoke production rate during test including burner.*

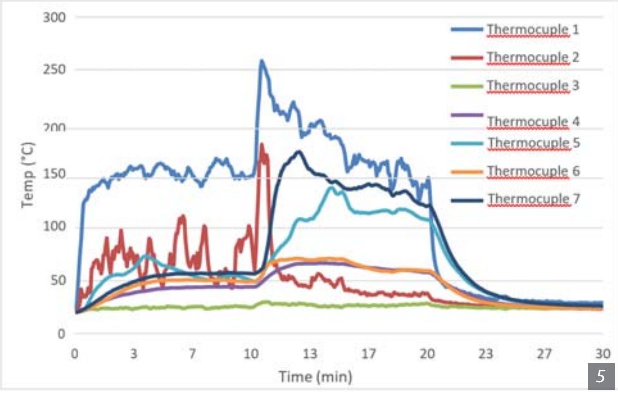


*Figure 5: Gas temperatures in the door opening and temperatures on the external panel surfaces during the test. Position of thermocouples were according to table 2:*

TABLE 2: SUMMARY OF THERMOCOUPLE POSITIONS

| Thermocouple | Position |
|---|---|
| 1 | Centre of doorway at a height of 1900mm |
| 2 | Centre of doorway at a height of 1500mm |
| 3 | Centre of doorway at a height of 1000mm |
| 4 | Centre of right wall panel, external surface |
| 5 | Centre of rear wall panel, external surface |
| 6 | Centre of left wall panel, external surface |
| 7 | Centre of ceiling panel, external surface |

TABLE 3: CALCULATION OF SMOGRA FOR TRANSPARENT AND PRINTED TEXLON® ETFE FOIL CLADDING SYSTEMS

| Product | Peak SPR (m²/s) | Time to peak SPR (min:s) | SMOGRA $10^{-4}$(m²/s²) |
|---|---|---|---|
| transparent | 1.77 | 20:00 | 14.8 |
| printed | 3.12 | 19:44 | 26.4 |

## Conclusion

The product called “Texlon® ETFE system”, in relation to its reaction to fire behaviour, showed a very limited contribution to heat and smoke production during the test. No visible flaming in the material was observed. No burning droplets were seen during the test. No flash over occurred.

For classification of building cladding systems exposed to fire it is not sufficient to focus on material performance and material tests only but to understand the reaction to fire of the system. Today the significant potential and contributions to safety are not taken into account when membrane structures are discussed. The small room test published in ISO 13784-1 provides evidence regarding the response of membrane cladding systems, ETFE foil cladding systems in particular, in case of fire scenarios. Even though there are no classification criteria given in ISO 13784-1 except flash over which does not allow for a normative clause, informative advice should be given in an upcoming standard. Since the response of membrane structures is fundamentally different from stiff building cladding materials, research towards the development of criteria derived from tests of the whole cladding system according to ISO 13784-1 is strictly recommended.

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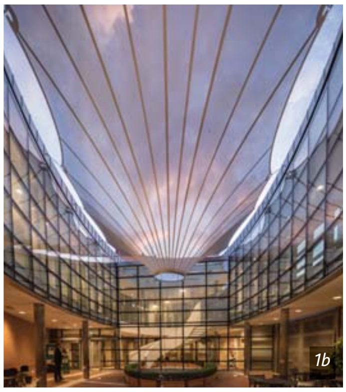
## SCENIC FUNNEL-SHAPED SHADING STRUCTURE

# Membrane cover for the internal courtyard of the Roman headquarters of LUMSA

## Rome, Italy

1a



1b

*LUMSA (Libera Università degli Studi Maria Ss. Assunta di Roma) is a public non-state Italian university formed on Catholic principles. It is the second oldest university in Rome after Sapienza and was founded by Luigia Tincani in 1939. LUMSA is accountable to the state university system and awards qualifications equivalent to those issued by state universities. These centres support research, seminars and conferences in conjunction with Italian and international colleagues from the most prestigious universities in the world. LUMSA is a member of the Agency for the Promotion of European Research (Agenzia per la Promozione della Ricerca Europea - APRE), part of the EURAXESS network - Researchers in Motion - and Eduroam (Education Roaming). It is located in Rome and occupies an architectural complex in the centre of the capital which also includes the historic building currently hosting the secretariat, the object of this construction.*

### Context

Focus of the project and the scenic funnel-shaped shading structure, designed by Arch. Vittorio Petrucci and built by Canobbio Textile Engineering, which protects the elliptical void of the building, wanted by the client to protect the internal courtyard and transform it into a new protected space, functional both for welcoming and for gathering students. (Fig. 1) In this way, in addition to making the open space usable even during the summer months for the usual educational activities, an additional place has been created for any cultural events.

### Project

This is a removable roof of approximately 80m²: approximately 15m x 8m and 3m high. The structure is constrained in the upper perimeter by thirteen points anchored to an existing reinforced concrete ring. (Fig. 2) In the lower part of the cone, a steel ring keeps the roof in tension towards the centre of the courtyard, stabilizing the membrane in the event of wind or adverse weather conditions. Greater stability is also given by a series of cables fixed to this central ring and anchored to the ground to a steel cylinder. (Fig. 3)

The formfinding of the roof, the statical analysis and the cutting pattern are designed with specific software modules for the lightweight structures. The worst situation analysed in the static analysis is the upward wind defined in accordance to the local rules, where the forces needed more attention to guarantee the safety of the textile structure (Fig. 4).

### Membrane

The shading roof of the courtyard of the Roman headquarters of LUMSA is made with the latest generation Frontside Print 371 textile composite membrane from the Serge Ferrari Group, designed for large-scale works and developed to ensure high durability over time, with the same initial lightness performance and sun protection. (Fig. 5) The Précontraint® technology, patented all over the world by the Ferrari Group, in fact maintains the biaxial tension of the composite membrane during the entire production cycle, in order to obtain a performing material from the point of view of dimensional stability, mechanical strength and thickness and surface flatness. In this way, Frontside Print 371 protects from the sun's rays, preserving the light contribution unaltered and limiting glare for a long time, while also maintaining the mechanical qualities and resistance to atmospheric agents unchanged over time. Lightweight and 100% recyclable, as well as possibly printable with ad hoc graphics.

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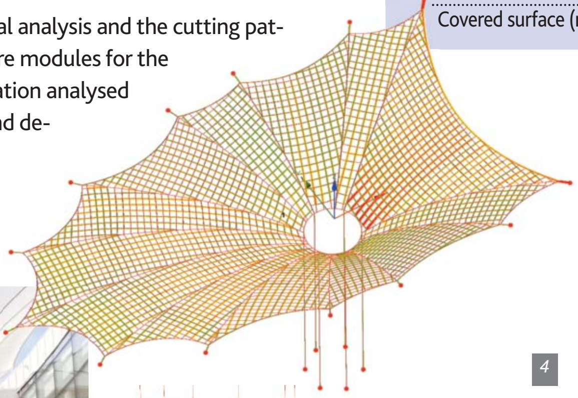
| | |
|---|---|
| Name of the project: | LUMSA |
| Location address: | Borgo S. Angelo, Rome, Italy |
| Client (investor): | LUMSA University (Libera Università Maria Santissima Assunta) |
| Function of building: | Education |
| Type of application of the membrane: | Shading cover of the inner court |
| Year of construction: | 2018 |
| Architects: | Vittorio Petrucci |
| Structural engineers: | eng. Alessandro Rizzo |
| Engineering of the controlling mechanism: | eng. Alessandro Rizzo |
| Main contractor: | Sistema Tetto S.r.l. |
| Contractor for the membrane (Tensile membrane contractor): | Canobbio Textile Engineering S.r.l. |
| Supplier of the membrane material: | Serge Ferrari |
| Manufacture and installation: | Canobbio Textile Engineering S.r.l. |
| Material: | Serge Ferrari's micro-perforated Frontside Print 371 |
| Covered surface (roofed area): | 80m² |

*Figure 1a-b. Bird view and interior view of the protected courtyard*
*Figure 2. Membranes upper perimeter anchored by thirteen points to an existing reinforced concrete ring.*
*Figure 3. Lower part of the cone kept in tension by a steel ring which is anchored by a series of cables to the ground to a steel cylinder.*
*Figure 4. 3D modelling showing the membrane stress and cable force*
*Figure 5. Clouds visible through the Serge Ferrari's micro-perforated Frontside Print 371*
*© pictures: Andrea Liverani / drawings: Canobbio Textile Engineering srl*



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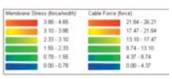

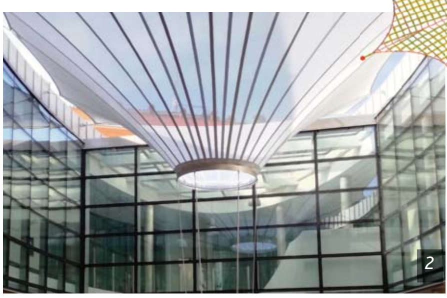

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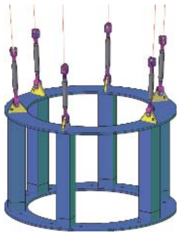


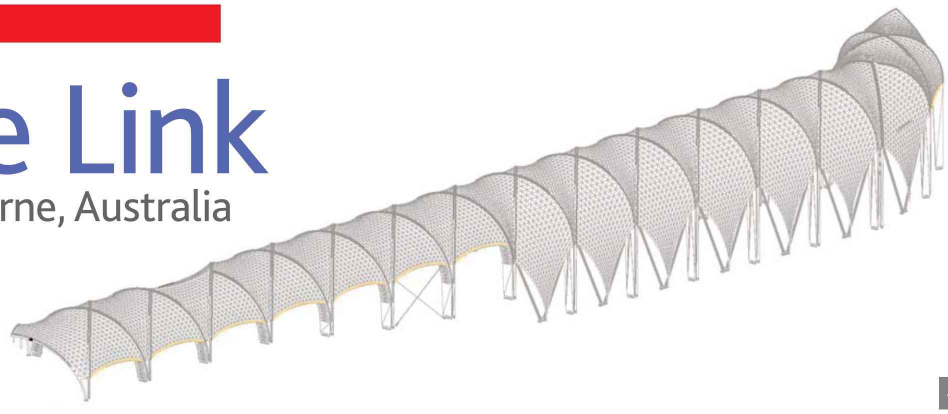
3

5

*Designed to blur the lines between the retail, commercial and leisure zones of Chadstone's high-end fashion shopping precinct with the newly opened Hotel Chadstone Melbourne MGallery by Sofitel, The Link transforms part of a multi-level car park into a cathedral-like promenade for shoppers and hotel guests.*

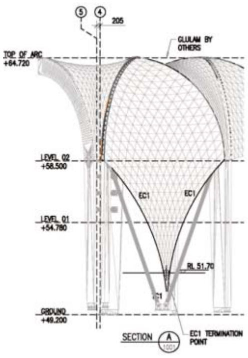
# The Link

## Melbourne, Australia



2

## THE CATHEDRAL-LIKE WALKWAY FOR CUSTOMERS AND HOTEL GUESTS



4

1a

1b

3a

3b

5a

5b

*Figure 1a-b. The 100m arched walkway The Link integrated in the urban environment.*
*Figure 2. Isomeric view of the tensile fabric membrane over the glulam arches.*
*Figure 3a-b. The high translucent canopy seen from outside (left) and inside (right).*
*Figure 4. Partial elevation of membrane covering with catenary cables and bracing.*
*Figure 5a-b. The canopy as a cathedral-like nave defining and protecting the pedestrian access to the shopping precinct.*
*Photos © Peter Bennetts / Drawings © MakMax Australia*

### Project

Commissioned by leading Australian real estate investment trust Vicinity Centres, and completed in October 2019, The Link is a 100m arched walkway that soars up to 15m above the pedestrian zone and is covered with 1750m$^2$ of high-translucency THV coated PTFE fabric (Fig. 1).

### Design & engineering

The designing architect's vision was to complement Chadstone Shopping Centre's existing vaulted glass roof with an iconic structure created with glulam (Glued Laminated Wood) timber arches, covered with a semi-translucent tensile fabric membrane (Fig. 2).
The design and engineering challenge faced by MakMax Australia on The Link was to deliver a premium tensile membrane finish to complement the projects' luxury look and feel. With the aim to link the new 5-star Hotel Chadstone to the Chadstone Shopping Mall – the membrane finish had to embrace the high-end, luxurious aesthetic of the project.

### Material & detailing

Chosen for its high-strength and pliable ePTFE fibres to optimise light transmission and diffusion, the 1750m$^2$ of high-translucency Sefar Tenara 4T40HF THV coated PTFE canopy protects customers, guests and visitors from the weather, while still providing a light, airy and inviting pedestrian walkway (Figs 3-4).
A strong design focus was made to the membrane and catenary cable detailing, ensuring all fixings were minimal and discreet, while still offering the strength and flexibility required for installation. This task was made more difficult by the multi-planar fixing surfaces each glulam leg provided and the restrictions of fixing to glulam itself. The resulting details look light and inconspicuous, fitting in with the language of the rest of the design.

### Erection

Having limited site-access was a challenge overcome in the installation phase. The structure needed to be integrated into the existing (and operational) premium shopping centre and required being constructed directly on top of several layers of basement.
The breathtaking visual effect that results from the high-translucency fabric and light finish of the glulam timber, provides an incredible sense of openness, while maintaining architectural continuity between the hotel and the mall. The high transverse arches create an almost cathedral-like nave that draws pedestrians along and upwards via a series of escalators into the alter of Melbourne's Fashion Capital, Chadstone (Fig. 5).

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| | |
|---|---|
| Name of the project: | The Link |
| Location address: | Chadstone Shopping Centre, Melbourne, Australia |
| Client (investor): | Vicinity Centres |
| Function of building: | Walkway |
| Type of application of the membrane: | Glulam arch supported canopy |
| Year of construction: | 2019 |
| Architects: | Make Ltd (concept) / Cera Stribley (project architect) |
| Consulting engineer for the membrane: | MakMax Australia |
| Main contractor: | The Hickory Group |
| Contractor for the membrane (Tensile membrane contractor): | MakMax Australia |
| Supplier of the membrane material: | Sefar |
| Membrane manufacture and installation: | MakMax Australia |
| Material: | Tenara 4T40HF (High Translucency THV coated PTFE fabric) |
| Covered surface (roofed area): | 1750m$^2$ |

The project has won several awards across multiple industries for the various contributors. As the membrane designer, engineer and installer, MakMax Australia received the Specialised Textiles Association (Aust) 2020 Award For Excellence: Tension Structures 250m$^2$ to 2000m$^2$.