First prototype of a foil façade of equal frame modules covered with mechanically pre-stressed foil

ETFE Façade
contents

PROJECTS

4 Australia MAIKMAX AUSTRALIA
Transformation into a Green Void

5 Spain BAT BURO ARQUITECTURA TEXTIL
Textile Mall Parque Almenara

6 Italy UNIVERSITÀ DI NAPOLI FEDERICO II
Textile in interiors

10 Spain COMERCIAL MARITIMA L&Z
ARENAS & ASSOCIADOS
Tensile roof Orca Ocean Show

19 Spain LLORENS
A circular paraboloid The Castle

ARTICLES

12 ETFE Façade
First prototype of a foil façade of equal frame modules covered with mechanically pre-stressed foil.

14 FAILURE of fabric reinforced membranes
A yarn based modelling approach

18 INDUSTRY SUPPORTED PHD
started at Newcastle University
A pragmatic approach to determining the mechanical behaviour of structural fabrics.

RESEARCH

MISC

9 LITERATURE
New Tent Architecture - ETFE Technology and Design - Kengo Kuma

24 PRESS RELEASE
Good design award 2008
3 awards for FabriTec Structures Westfield Wondon
Edito  Since the last TensiNews issue both an Annual General Meeting (10th November, Stuttgart) and a Board Meeting (2nd February, Brussels) have taken place.

In Stuttgart fifty one TensiNet members attended the lectures, the Annual General Meeting and the Working Group Meetings and afterwards visited Labor Blum. During the Partner Meeting the new board was elected: Heidrun Bögner-Balz as Chair, Bernd Stimpfle, John Chilton and Stefania Lombardi as Vice-Chairs and Marijke Mollaert as Executive Secretary.

As agreed during the second Partner Meeting in 2006 the class of Founding partners does not exist any longer. Partners pay the full 2400€ membership fee. A new class of Associate partners has been introduced: these are the Working Group Leaders, the Schools and Universities which actively contribute to TensiNet's daily work and “small firms” which are invited by the Partners according to their specific expertise.

During the Partner Meeting it was proposed to choose for the next TensiNet Symposium an Eastern European country. The exact location is not decided yet.

The next Partner Meeting is planned on Monday the 15th of June just before Techtextil 2009 (Frankfurt from 16th till 18th June). The Working Group ETFE (Rogier Houtman) will meet the same day. The Student Award ceremony takes place on the 15th in the evening. The Working Group Disaster Relief will be activated. Caroline Henrotay (VUB) will coordinate this Working Group.

During the Board meeting it was decided that the TensiNet Association should put extra effort into increasing the number of TensiNet members: all current members should contact candidate members they know personally. TensiNet should promote its Working Groups, should publish articles in local professional magazines and become more visible during events, fairs and symposia. To support these actions a new TensiNet flyer is available at http://www.tensinet.com/files/General_information/FLYER_2009_2.pdf

From now on individual issues of TensiNews, with the renewed layout, will be on sale at the price of 15€. New issues will be announced on the website with a table of content. Abstracts of important articles will be put on the website with a reference to the corresponding TensiNews on sale. National and local professional magazines will be informed about the renewed TensiNews.

A proposal for the standardisation of “materials, fabrication and installation of membranes” has been sent to the standardisation communities (TC 250) of the European countries as a first step in establishing a EUROCODE. National representatives are Juan Monjo and Ignasi Llorenz for Spain and Portugal, Roberto Canobbio and Alessandra Zanelli for Italy, Matti Orpana for Finland and the Scandinavian countries, Marc Malinowski and Françoise Fournier for France, Heidrun Bögner-Balz, Bernd Stimpfle and Henric Leuer for Germany, Marijke Mollaert for Belgium, Rogier Houtman and Arno Pronk for The Netherlands and John Chilton and Peter Gosling for the United Kingdom. They will follow up the handling of the proposal for a EUROCODE.

The Annual General Meeting 2009 will be held on the 30th of September during the IASS 2009 conference in Valencia. Joint to the Annual General Meeting the results of the Working Groups will be presented and interesting recent projects completed by TensiNet members will be reviewed. A slideshow will be made and afterwards put on the website.

With this short summary of meetings, discussions and future action points we hope to reinforce the presence of Tensile Surface Structures on the market and to strengthen cooperation in research.

Marijke Mollaert

Calls

ICSA2010

1st International Conference on Structures & Architecture
Guimarães, Portugal - 21-23/07/2010

Call for Mini-Symposia & Special Sessions
> before 30 April 2009
Call for Abstracts
> before 31 May 2009
Call for Associated Events
> before 30 June 2009

Forthcoming Events

International conference TEX TEH II - 2009 Bucharest, Romania 07-08/05/2009 www.certex.ro/conference_texteh2.htm
Workshop Textile Roofs 2009 Berlin, Germany 11-13/06/2009 www.textile-roofs.com
International Trade Fair & Symposium Techtextil 2009 Frankfurt, Germany 16-18/06/2009 techtextil.messefrankfurt.com
International Conference Structural Membranes 2009 Stuttgart, Germany 05-07/10/2009 congress.cimne.upc.es/membranes09
Sydney Customs House has rolled out the green carpet to unveil a unique addition to its architectural history. It has been given an ultra-modern edge with a futuristic yet organic 3D structure known as the “Green Void”, the latest collaboration between MakMax and Chris Bosse of LAVA.

The lightweight Lycra sculpture hovers within the Customs House atrium, taking in Café Sydney's top floor position stretching to the model of Sydney incased in the glass floor at ground level. The translucent fabric allows ample amounts of sunlight through from the atrium some 5 floors above creating a surreal experience as the surroundings take on a lime green glow. At night the structure is illuminated to take on the look of lava bubbling up from a volcano.

MakMax and Chris Bosse have previously worked on projects such as the Moet and Chandon Marquee and POL Oxygen stand and more recently the MTV Music Awards set but nothing could compare to this most recent collaboration.

This is the most ambitious Lycra structure they have ever attempted. Being a heritage listed building many challenges were faced in the design process. They had to create a surface floating in space, supported by a heritage listed façade which they were not allowed to permanently anchor to, as well as support a fixed fabric edge that was not excessively heavy. The end result is a credit to the engineering design, patterning and fabrication process.

The project shows a new way of digital workflow, generating space out of lightweight material in an extremely short time. The computer-model feeds directly into the finite element software for generation of true fabric form which marries with the manufacturing process.

Lycra has been given new life with applications such as custom designed fabrics that stretch the possibilities of modern architecture. The fabric is a standard 80% Nylon/20% Lycra which is sourced from a manufacturer traditionally to dealing with dancewear manufacturers.

With sustainability being at the forefront of every architect’s design concept MakMax has been leading the way with bespoke tensile membrane structures and use of minimal materials. The total fabric weighs a mere 45Kg and is stretched over 12% past its original size to create its final shape. The use of such fabric allows it to be folded and fit inside a sports bag, yet has enough elasticity to fill a volume of 160m³. The total surface area is 233m². Minimal amounts of Aluminium and hardware were a necessity to enhance the fabrics natural curvature. The fabric is supported by only five rings. The complete structure including the Aluminium edges weighs 210Kg.

The form was taken from an architectural model developed by LAVA. Utilizing force density shaping and elastic analysis the final shape was found to complement ring supports. Intricate patterns limited by the 1.5m fabric roll width create the structures form. Cutting patterns were developed through scribing geodesics through the structure at strategic locations and flattening using an energy method more able to handle the highly curved surface. The riggers dubbed the structure 'Shrek's ears' which is a great example of digital media being translated into fabric design.

The Green Void oozes charisma and will remain on display until mid 2009.

Daniel Cook
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For the food court, three big conical roofs were planned in order to create vast shadows. At the lower points the membranes are anchored on the roof of the mall structure and the tops are supported by three main masts - one for each roof. The overlapping of the three membranes was designed to create a more dynamic visual result. As an immediate outcome of these ideas and also due to the size of the roofs (each one of the two smaller structures is 800m² Ferrari 1202 and the biggest is 2.000m² Ferrari 1302) high loads appeared. This requires a high prestress (more than 2.000kN in some cases) and hence a strong primary structure and heavy duty cables. The final result still seems light within the large spans (in the central roof more than 60m). All the masts and cables were placed exactly on the appropriate concrete pillar heads: some of the anchorage points on the slab were reinforced with additional steel frames and thicker slabs so that the load transmission was correct. Steel plates for masts and cables were installed during the execution of the slabs, to assure a high quality load transmission. Some of these plates did weight over 800kg.

were used and at the top of the main masts the position of a floating ring connected to the top was adjusted by tensioning with hydraulic devices. Each membrane was plotter cut and welded into one piece (even the 2.000m² one) in our factory, and crane folded in a precise way to allow an easy unfolding on site, at the right position. Cable sizes did not allow using reasonable pocket borders, so a clamping system was designed to allow the installation of the clamps and the cables on the ground, and the uplifting roof by roof in only one operation. Time needed for the installation of the food court roofs was one month, two weeks for the biggest and one week for each one of the smaller.

Restaurant
Ten more roofs were built for a specific restaurant. They were designed as inverted cones of about 80m² each, with an eccentric mast, and were manufactured in the workshop and installed in a very fast way since all the system works as a modular kit construction. Membranes were patterned, plotter cut and made in our factory in Ferrari 502 coloured fabric. Installation process on site took only one day per roof.

Bowling terrace
Finally a 600m² roof was designed and built for the bowling terrace, following similar criteria than in the food court ones. An articulated central arch created a significant shape in the middle, so it was easy to reduce loads on the membrane and the structures. This roof was made in Ferrari 702, and its geometry and size allowed a common pocket border solution, so the complete roof was designed, engineered, built and installed in only 1 month.

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Textile in interiors

In membrane architecture, we don’t talk enough about textile in interior architecture and furnishing, in particular about its wide possibilities in application of innovative systems of interior envelopes and partitions. Textile materials can contribute to articulate many different spaces, residences or offices, exposition spaces and showrooms, and generally in every occasions in which flexibility and constructive reversibility represent essential objectives: furnishings, shows, fashion parades, musical and artistic or cultural installations, commercial or fair manifestations, ceremonies or parties and so on.

Lightness and translucence of membranes, together with constructive elements in aluminium, steel or wood which act as supports, are properties that make effective application of textile elements and systems in furnishings and interior architecture or in creation of temporary, removable or transformable installations.

Stretch textile materials are often utilized in interiors. In fact they have many invaluable qualities for this use. Stretch textiles take the form in dependence of locations of supports and also of applied tensions, so they mould directly on anchorage points; in different cases stretch textiles avoid difficult problems in design with fabrics or membranes, that are the question of form-control and the other question about cuts of fabrics, so when installations have small dimensions it’s possible to solve these problems. In fact, the problems of cuts and assembly between different parts of fabric remain essential questions in large projects or installations, in which membrane is cut and then it is assembled; another essential problem is about modelling, that is realized and controlled by construction of mock-up, three-dimensional scale models or virtual simulations.

Textile membranes have a grade of elasticity that varies according to composition of material; in particular, it can vary from 3% to 30% till 200% of elongation for stretch membranes, besides when elongation is greater the translucence of membrane becomes greater too. Stretch fabrics, like cotton, nylon, polyester, contain a variable percentage between 3% and 30% of an elastic polyurethane fibre that is called spandex or elastan.

Among stretch fabrics for interiors, Nylon has excellent mechanical qualities, high coefficient of elasticity, toughness and resistance to abrasions or lesions and impacts. Moreover, Kevlar is a fabric that is included in particular class of special Nylon; it has high resistance to tractions and impacts, furthermore it has a unique combination of qualities, as resistance to warm and fire or as high absorption of vibrations, that has allowed designers and constructors to find answers for many problems, which are esteemed hard to solve in field of organic fibres. Moreover, today fibre in PTFE (polytetrafluoroethylene), with trade-mark TEFLON, is very often used because of its excellent qualities about mechanical, thermal and chemical stability; another excellent fibre-mix is PTFE and glass, with trade-mark TEFAIRE that is a good and innovative alternative, also in order to have economic benefits.

INSTALLATION “Vesuvio libri”
at the library “Pisanti”,
S. Giorgio a Cremano, Naples

In the work for the interiors of the library “Pisanti”, carried out and realized in 2002, the installation is inspired by the Parthenopean volcano, also in its name “Vesuvio libri”; it is originated from the idea of a symbolic analogy with the volcanic eruption that in this project becomes production and distribution of culture. The visual analogy is possible thanks to the ability to create with membrane a shape that remembers an upside-down volcano, so books go out from its mouth, in the same time it features the space and it creates an original internal covering for the sale room. The installation of covering in an “upside-down volcano” belongs to a larger project that includes interior placing for many bookshop locals, in which was provided design and realization of exhibitors for book-sales and different typologies of sails, that have functions of covering and furnishing for interior rooms. The bookshop is organized in different functional areas, that are entrance, multifunctional area, communication area, storehouse and specific exhibition areas (Figure 1). Common and unifying vaulted tenso-structure elements were provided for different rooms. They have different dimensions and radiuses in order to adapt themselves to the geometry of the rooms; moreover, the structure of sails is also utilized to support canalizations for the plans and in order to regularize the height of rooms. Another specific function of the membrane structures in this work, thanks to the translucence of fabric, is supplying useful reflecting surfaces for lighting the rooms, in order to improve visual comfort in interiors; furthermore a detailed study was made for the right collocation of the lights that illuminate books on sale and for the internal paths from a room to another.

In this work the fabric called TB Cottonfire C1, composed of 55% cotton and 45% modacrilic was employed; the weave is constructed from Ne 20-2 yarns in the warp direction (30 threads/cm) and Ne 8-1 yarns in the weft direction (20 threads/cm); the Cottonfire fabric weighs 360gr/m² and its width is 195cm. Moreover,
Membrane architecture

Furthermore, textile materials present very interesting behaviour in relation with light; in fact, all stretch fabrics or plastic membranes have different properties of light transmission, reflection and absorption, so they can generate particular lighting effects, for instance making surfaces, that can be external envelopes or interior partitions in architectonic spaces, on which solar radiation filters and through which artificial lighting is modulated. In design of interior architectures, textiles contribute to realize flowing and soft spaces, whether for lightness of elements or for natural luminosity of materials, in particular when they are applied in division of different spaces with different functions, or in staging for expositions and events that request original visual effects.

On international scene of design with textiles for interiors, protagonists are American designers, architects or engineers, and also manufacturing companies that have experimented with use of fabrics in various occasions. In particular, Transformatit projects, produces and installs structures for interiors with tensioned fabrics; another American company is Dazian, which supplies a wide range of stretch fabrics able to open up new horizons for interior architectures, for instance directing attention to textile scenographies that give possibilities of different pleasure grades for many performances with visual originality. Among international design studios, FormTL, a German engineering firm, is particularly active in textile design, because of its large experience in textile design and membrane structures; moreover, American designer Gisela Stromeyer uses stretch fabric “spandex” for many and different installations; she works with a variety of options for fabrics, that can be translucent or transparent, coloured or white together with particular lighting effects.

In Italy the use of textiles in interior architectures is not enough widespread yet, also because of insufficient presence of studies with specialization in textile design and few operative industries or companies for production, supplying and manufacture of membrane structures. Another impediment to larger diffusion of membrane architecture in Italy is due to the lack of a normative reference, in particular for big coverings, external envelopes and large constructions, which are more subject to the problems of structural safety and stability, resistance to weather or fire and so on.

Among the architects who pay more attention to the possibilities of using textiles in architecture, Aldo Capasso distinguishes himself by a wide research work about membrane architecture, in the Laboratory of Lightness Technologies in the University of Naples, and moreover by some projects that exalt textiles for their versatility and their inclination for fitting out or furnishing the interior.

These works, thanks to the use of a fabric like cotton fibre, articulate spaces with different features in order to add modern value, operating on pre-existent elements with different modalities: in historic and artistic scenes textiles add an innovative accent in a light way without any grave invasion; while, in places of new constructions textiles exalt spatial peculiarities giving character to rooms or scenes, underlining a dimension or a perspective rather than another architectonic element and are able to design new shapes of spaces. So these works become emblematic of design modalities that answer to different needs: one of these works is permanent furnishing and the other are temporary fitting-outs. The first one of these works is the design of interiors for the library “Pisanti”, in S. Giorgio a Cremano (Naples); the second one is the fitting-out for the prize-giving manifestation in Camera di Commercio in Naples and the last one is the installation for the exposition about “Impresa Donna”, both located in a central room of the Palazzo della Borsa in Naples.

Figure 1. Sketches for the installation of “Vesuvio libri” at the library “Pisanti”.
Figure 2. 3D design of the “Vesuvio libri”.
Figure 3. Interior view of the “Vesuvio libri”.

The finish is applied through immersion with fluorocarbonic resin with processing Scotchgard and “Sanitized”. The sewing parts of fabric were cut according to the geometry of the graphic design and made ready. Assembly of installation consists in joining tambourines together with steel cables that are fixed at anchorages in the walls of the building structure. Connections are at a height that allows regulating the tension of the fabric in order to obtain the correct spatial configuration of membrane structure. On one side fabric has a punctual anchorage at perimetric walls, on the other side it is anchored in four points at a steel disk that is fixed at the exhibitor of books thanks to a steel hook. The base of upside-down volcano coincides with the middle of the room, where the different parts of fabric are connected through steel connection systems at the support structure, so the membrane takes designed shape and lets you see the internal side of textile volcano, while light can pass through textile covering (Figure 2).

In this way, the diffuse light through the membrane was utilized together with the light that is projected from lamps onto the external surface, so it is possible to have more light in the room. In conclusion, the membrane covering also evokes lunettes on walls surrounding the room, which are decorated with pictures of Parthenopean Volcano, from Goethe’s work to contemporary artists’ works (Figure 3).

<table>
<thead>
<tr>
<th>Name of the project:</th>
<th>Vesuvio libri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location address:</td>
<td>Villa Bruno, S. Giorgio a Cremano, Naples, Italy</td>
</tr>
<tr>
<td>Client (investor):</td>
<td>Società Renato Pisanti srl</td>
</tr>
<tr>
<td>Function of building:</td>
<td>Library</td>
</tr>
<tr>
<td>Type of application of the membrane:</td>
<td>Up-side down cone structure</td>
</tr>
<tr>
<td>Year of construction:</td>
<td>2002</td>
</tr>
<tr>
<td>Architects:</td>
<td>Aldo Capasso and Alfonso Mauro, Carmen Terracciano (collaborators)</td>
</tr>
<tr>
<td>Structural engineers:</td>
<td>Baku Group, Naples</td>
</tr>
<tr>
<td>Manufacturer and installation:</td>
<td>Salvatore Sessa, Naples</td>
</tr>
<tr>
<td>Material:</td>
<td>TB Cottonfire C1</td>
</tr>
<tr>
<td>Covered surface:</td>
<td>56m²</td>
</tr>
<tr>
<td>Cost:</td>
<td>6000€</td>
</tr>
</tbody>
</table>
The work for the installation “Impresa Donna” was designed in 2004 and it was thought like a sculpture of light, that had the function of exhibitor for pictures and documents which are collected for the exhibition about “Women in Commerce” in Italy. Objects in the exhibition are protected by a singular up-side down umbrella, realized with a translucence fabric, from which a set of cables starts in order to connect symbolically the exhibition about contemporary commerce with past commerce, located at a higher level of the exhibition room. The architectural element becomes an innovative sign that sets well in an evocative architectural frame with an important historical and artistic value (Figure 4). The fitting-out has different functions, like functional, scenographic and symbolic one. The functional element results from an indirect lighting system that is provided on the membrane, so the membrane becomes an enlightening surface for exhibition planes below; in fact some lights are provided below the open umbrella, and one is located upon the umbrella with coloured light that spreads softly in the room. Moreover, in order to avoid the problem of light dispersion coming from down and in order to avoid having excessive light in the room, that could obstructs the visual perspective of space, a “lamp-shade” was designed, that is a textile doubly curved surface which inserts itself on the up-side down umbrella and it completes the light sculpture. The artificial lighting system underlines the global image of the fitting-out and the historical lexicon of the central room in Palazzo of Exchange. Really, the light is transmitted to the exhibition plans below and in the same time it is diffused in the surrounding space in order to exalt the historical and artistic context where the exposition is taking place. Circular and up-side down the big umbrella evokes image of a flower, which becomes a scenographic element: a wide polygonal base for exhibition.

For the fitting-out of the prize-giving manifestation in the Camera di Commercio in Naples (2002) a tensioned textile was realized, which was located in the middle of the room like a tensioned structure to cover the protagonist place of the manifestation. The sail, made in TB Polibox (FR-DIN 4102) is composed of 100% PES, it weighs 190g/m² and has a width of 157/235cm. It is constructed by warp yarns 330 dtex-24 threads/cm and weft yarns 330 dtex-20 threads/cm; moreover, the finish is applied by coating it in two phases with PU flameproof resins, with hydro and oleo-repellent “Teflon” treatment and it has a light solidity 5/6, depending on the colour of fabric. Membrane is articulated on a plan that is inclined with respect to the rectangular plan of the room. The sail is anchored in high points through cables that start from four points, which are in tension by rolled up cables at the capitals of the columns that surround the room; low points, instead, are tensioned by cables that are anchored in the four corner points of the square floor where the ceremony takes place. Furthermore, at the low points of anchorage four lights are located, which work together in order to light up the sail from bottom up, and diffuse uniformly the light in the room, thanks to clear and reflecting surface of the membrane. The sail has a perimeter of 2,75m by 2,75m; it is based on a square plan with eight points of anchorage, four high points and four low points. The difficulty of assembly and realization, in this case, was solving the problem of anchorage for the tenso-structure without intervening in the pre-existent structures, so it was tried to use elements like supports without leaving any traces after dismantling. The choice of the solution was a system of cables, which were rolled up on columns that surround the room, at the height of the capitals, so it was possible to have a correct configuration of the sail and in the same time it was possible to hide the view of anchorages. The sail dominates and shows the area for prize-giving, in this way it gives to the platform an evocative image because of the reference to lightness of flight; a symbolic presence linked to the most important moment of manifestation, that is the prize-giving to the person who had a recognition for own devotion to work. The fabric does not only exalt visually a physical space but also celebrates a meaningful moment (Figure 5).
CONCLUSION

Membranes become protagonist thanks to many qualities and features that make possible a correct functionality for different architectonic spaces and they can give a particular meaning to places where they are installed. From the works we have described here, we can derive some considerations about peculiar aspects of textiles, in particular about their adaptability and their facility to furnish, as well as their reversibility. So we can say that membranes are very easy to adapt to different spaces and in the same time they are able to modify these spaces because of given needs, for instance expanding or restricting delimited spaces, in height or in depth. Moreover, membranes can be included with lightness in contexts that are yet full of values and strong signs, without any volumetric invasion in consolidated spaces; furthermore, membranes are easily usable so they make places recognizable and perceptible in a direct way, avoiding disorientation like it could happen in places which are not well designed. In conclusion, it’s possible to state another and not less important reflection about the realisation cost of these installations: they are realised and constructed by local artisans, moreover they didn’t request excessive costs and long time for construction, also because generally membranes lend themselves to different kinds of work or adaptation, in fact they often provide different solutions to practical problems that frequently occur on the building site and which must be solved even in phase of realisation.

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Pictures of “Vesuvio Libri” are published here. For pictures of other works, realized in Palazzo della Borsa, please contact the author.

LITERATURE

ETFE Technology and Design

Author: Annette LeCuyer

ETFE foil has recently become an important material for the cladding of technologically sophisticated and innovative buildings. This material is very thin and lightweight and, when used in air-filled cushion assemblies, has enormous strength and a range of adaptive environmental attributes. ETFE cushion enclosures became widely known primarily through Grimshaw Architects’ Eden Project and Herzog & de Meuron’s Allianz Arena, and they are being used on the spectacular swimming stadium for the 2008 Olympic Games in Beijing, the largest ETFE building envelope in the world so far. This book is conceived as an in-depth introduction to the characteristics of ETFE and its applications in construction. Project examples explore in detail the specific characteristics of ETFE building skins in the areas of structural behavior, light transmission, insulation, acoustics, fire engineering and environmental modification.

Language: English  □ Size: 230.4 x 23.5 x 2.3 cm, 397 illustrations, 246 in color, 160 pages (hardcover)  □ Editor: Birkhauser  (August 2008)  □ ISBN 978-3-7643-8563-7  □ Internet sale: www.springer.com/birkhauser

Kengo Kuma

Breathing Architecture

Creative Resources for Shade, Signage and Shelter

Author: Volker Fischer, Ulrich Schneider

The teahouse of the Museum of Applied Arts Frankfurt

Kengo Kuma’s Teahouse is a masterly reinterpretation of a classical Japanese building type. Delivered in August 2007 for the Park of the Frankfurt Museum of Applied Arts [a Richard Meier Building], Kuma’s innovative structure in flexible, semi-transparent, ‘breathing’ Tenara-Membrane - inflated by means of a pneumatic system to a blossom like form - houses in the interior the classical elements for Japanese tea ceremony. Integrated LED technology allows the use of the teahouse at night; the interior can be heated by way of the membrane. The monograph, including an original text by Kuma himself, gives an in-depth documentation of this lyrical temporary structure – an outstanding example of ephemeral architecture, combining poetry and technology - with many unpublished sketches, technical plans and with splendid colour photographs.

Tensile roof Orca Ocean Show
Puerto de la Cruz, Tenerife Island, Spain

Loro Parque is one of the biggest tourist attractions of the Canary Islands. They had the ambitious idea to show the first orca spectacle in Spain. For that purpose Loro Parque desired to have an impressive exhibition site, in accordance with the importance of the show. In this way, Loro Parque asked for a roof design to cover the orcas’ swimming exhibition pools. Comercial Marítima, as Contractor, and Arenas & Asociados, as Design Engineers, submitted the winning design. The design criteria specified by Loro Parque were fully met by Comercial Marítima and Arenas & Asociados’ design. Loro Parque asked for a roof, comfortable for the spectators - protecting them from rain, wind and excessive sun - and functional for the orcas - meaning that the roof was not a barrier in case the orcas had to be evacuated for medical reasons. The roof design pleased the owners, not only because it satisfied their requirements, but it gave a fantastic view to the ocean horizon. It is important to add that the design of the roof was restrained by the fact that the foundations and the stands had already been designed. But this was not an obstacle for reaching a good design!

Steel structure
The supporting structure for the tensile members is built in steel, except the foundation, obviously built in concrete. The elements that constitute the steel structure are: two main arches, ten diaphragms between them, ten ribs with its supports avoiding buckling in the arches, eight masts and a V-beam, and the slender beams that brace the ribs (Figure 1).

Arches
The pair of arches, with concrete abutments, span 64m with a sag of 16m, which means a sag/span ratio of 1/4. At the highest points the maximum transversal span between the arches is materialized, being a distance of 22m. The arches have been designed as a parabolic curve, which is an approximation for the reversed funicular shape. Both arches, internal and external have a hollow box section with a height of 600mm and a width of 700mm, with a thickness of 10mm and 12mm respectively. The shape of the arches is very interesting because the external faces show a singular play of light and shadows while the internal face is plane to simplify the steel connections. The slender diaphragms, with a square section of 200mm, have been arranged between the arches to avoid the buckling of the arches and to support the compressive strength due to the tensioning of the tensile membrane. Thanks to the lightness of the arches they could be built by means of a crane and auxiliary steel towers acting as a temporary support (Figure 2).

Ribs
Another interesting part of the structural frame that supports the tensile membranes are the ribs. They have a parabolic semi arc curve, they span between 21m and 32m and brace laterally the most stressed arch, being the inner arch. The ribs avoid fundamentally the lateral buckling of the arch, and in a minor way, the buckling in its own plane, due to the flexural stiffness of the ribs. The buckling safety is not the dimensioning criterion for the arch. The external arch is braced to the inner one thanks to the diaphragms, although the external arch is less stressed than the inner one.

The ribs have a hollow box shape, with the upper flanges adjusted to the curvature of the textile which is attached to the ribs. These ribs have a width of 200mm and a height of about 600mm, with several sheet thicknesses depending on the span. The boundary ribs are very important, because they have to carry the unbalanced forces due to the stand membrane. That is the reason for introducing the bracing beams among the ribs. These bracing beams increase the safety factor of the ribs against lateral buckling (Figure 3).

Mast
The steel frame is completed with the masts, being a fixing point for the semi conical membranes. In the crown of the mast a connection system for the textile membrane with screwed bars was designed. These bars make it possible to adjust the tension in the membrane. The masts are 8m high and have a variable cross section, with convex flanges and concave webs having a maximum width and height of 250mm and 500mm respectively, at the fixing to the concrete frames of the stands (Figure 4).

Foundation
for the main arches
Finally, the membrane supporting structure is completed by the foundation of the arches, consisting of a surface foundation of 5m width, 8m length and 1.3m depth and a wall of concrete of 8.60m height placed on the footing. This solution was needed due to the presence of a service gallery between the exhibition pool and the training and medical pools. The level of the gallery was 8.60m below the surface, being the reason for having used a concrete wall for the foundation of the arches. Arising from the surface level, a prismatic concrete piece was designed having a full formal coherence with the section at the junction of the arches. As conclusion, we can say that this concrete basement makes that the union between the inner and external arch takes place 2.23m above ground level, permitting a suitable free vertical span for pedestrian flows, the piece having a human scale indeed (Figure 5).
Tensile structure
The tensile structure made with polyester PVC coated membrane Fluotop 1302 by Ferrari is the principal material of the roof. It has two differentiated parts. One part covers the Stand and the other covers the Exhibition pool. Both membranes were tensioned from the boundaries by means of tractels (Figure 6).

The Stand Membrane
The Stand Membrane protects the spectators from the environmental hazards, like sun, rain and wind. This membrane is anticlastic, organized in a succession of ridges and valleys, with nine semi conical shaped membranes in the backstage of the Stand. This membrane is subdivided in nine modules, each module being situated between two ribs of the steel frame. The modules are connected to the steel structure by means of spectra strands fixed to reeds at the ribs, clamps at the inner arch and bolts at the masts. All junction details were meticulously studied to avoid the filtering through of rain water in the exhibition pool, because this could infect the Orcas (Figure 7).

In order to avoid the introduction of unbalanced forces in the ribs, the tensioning of the Stand membranes was carried out in several phases and coordinated with the tensioning of the nearest modules. The textile Stand membrane was not only studied in a structural way. Throughout the design process we were always looking for the best aesthetical impression of the membrane covering, even when thinking on the details, like the seams for patterning. The conical shaped part of each Stand membrane module improves the structural response against external and internal loads due to its double anticlastic curvature in both ways, reducing the stresses in the membranes and the deformations of such membranes.

**Figure 1.** Steel structure.
**Figure 2.** View during the installation of the arches.
**Figure 3.** View during the assembly of the ribs.
**Figure 4.** Masts used as fixing points for the semi conical membranes.
**Figure 5.** Foundation wall and concrete piece.
**Figure 6.** Roof view.
**Figure 7.** Junction details.

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**Name of the project:** Tensile Roof for Orca Ocean Show  
**Location address:** Puerto de la Cruz, Tenerife Island, Spain  
**Client:** Loro Parque S.A.  
**Function of building:** Covering for spectators and for the orcas’ swimming exhibition pools  
**Type of application:** Protection against environmental hazards and light transmission  
**Year of construction:** 2006  
**Architectural Design:** Arenas & Asociados (Engineering Studio)  
**Comercial Marítima L&Z (Contractor)**  
**Project Manager:** José Luis Olcina  
**Structural Engineers and Consulting:** Guillermo Capellán/Santiago Guerra  
**Engineer for the membrane:** Arenas & Asociados  
**Membrane Structure engineering:** Comercial Marítima L&Z  
**Contractor for the membrane:** Comercial Marítima L&Z  
**Supplier of the membrane material:** Ferrari  
**Manufacture and Installation:** Comercial Marítima L&Z  
**Materials:**  
- Steel: 116000kg  
- Precontraint 1302T2 back PVDF 6010m²  
- ETFE of 200 μm thickness 75m²  
- Covered surface: 6085m²  
**Ratio:** 19 kg/m²
The Exhibition Pool Membrane

The Exhibition Pool Membrane is the most attractive, from our point of view, part of the roof. We understand this membrane in conjunction with the arches, give fantastic sights to spectators. Covering 1600m², this membrane introduces an innovation in membranes and it is the conjunction of PVC and ETFE membranes. The introduction of a central band of skylights made of ETFE single layer creates an interesting play of light and shadows over the exhibition pool (Figure 8).

The membrane was built in one piece at the Comercial Marítima L&Z Factory. As it was done in the Stand membrane modules, the seams order was identically studied to reach the impressive sight that spectators can receive from their seats in the stand. Once the Exhibition Pool membrane was manufactured it was delivered by ship from Vigo to Tenerife, and then raised by means of cranes to its position between the steel arches. The lightness of the membrane permitted to build the entire exhibition roof in one time. If another material would have been used, the construction phases would have increased with it's consequently delay in time. Construction time was a premise imposed by the Property, Loro Parque, and one of the reasons of choosing a membrane roof was precisely the fastness that the building of a membrane solution could provide. The rising of the membrane was made using first of all cranes and then tractels. The tractels achieve the slowest approximation to the arches, permitting to adjust the union with the arches in several phases. With this procedure the big membrane of 1600m² could be installed with the desired geometry (Figure 9).

As it was told previously, one of the innovating and interesting aspects of the roof is the conjunction of PVC and ETFE membranes. The ETFE membrane, with a thickness of 200μm, has a different Young's modulus from the polyester PVC coated membranes. For maintaining compatibility between the deformations of both materials, steel cables were introduced over the ETFE skylights. These cables were fixed to the connecting steel frame between the polyester PVC coated membrane and the ETFE foil (Figure 10). But not only were the steel cables needed for achieving the high stress flow between the lateral sides of the membranes, it was necessary to reinforce the narrow corridors connecting both sides of the membrane. Summarizing, the narrow corridors between the two sides of the membrane are high stress concentration points, solved by means of steel cables and membrane reinforcements.

The connection of the membrane to the steel arches was made using clamps, like it could be seen in the Stand membranes.

Conclusion

Comercial Marítima L&Z and Arenas & Asociados have projected and built an impressive roof that has fully satisfied the Property, Loro Parque, and that is enjoyed by the thousands of spectators visiting every day the Orca Ocean Show. A mixing of technology and beauty for an unequal environment and exceptional animals, like are Tenerife Island and the Orcas, respectively.

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Figure 8.
The Exhibition Pool Membrane – conjunction of PVC and ETFE membranes.

Figure 9.
View during the rising of the Exhibition Pool Membrane.

Figure 10.
Detail conjunction of PVC and ETFE membranes.
Other than the mentioned pneumatic cushion modules, there are also mechanically tensioned foil frames. They are created out of a single foil layer tensioned and then fixed to a rigid frame. The spatial curvature necessary to stabilise the foil can be achieved in different ways. One example is using arches fixed within the frame. A wide range of shapes and design of the foil structures can thus be created, varying from arch, or high-point supported structures to hypar-surfaces or just flat tensioned frame modules.

The first prototype of a foil façade, composed of equal frame modules covered with mechanically pre-stressed foil was installed in the Training Centre for the Bavarian mountain rescue division at Bad Tölz in Germany. In the commercial district of the town, a simple rectangular building was erected to provide a covered space for rescue training. Even helicopters were placed inside the building to simulate realistic rescue operations.

The building was designed by the architects Herzog + Partner from Munich. Its simple box-shape is accented by the arch-supported frame modules of the façade where the spatial curved and tensioned foil is reflecting the light in an unusual way, sometimes allowing an insight, sometimes mirroring the outside landscape. The façade is transferred into a three dimensional structure characterised by its high plasticity and visual depth.

The engineering, fabrication and installation of the façade were undertaken by Hightex GmbH from Rimsting in Germany. The modules were developed, tested and optimised for their use as a single layer façade. The basis of the frame structure is a Z shaped steel section. The upper web of the section supports the foil which, after tensioning, is folded around the section and connected on the diagonal web by clamp bars.

Afterwards the arched is pressed into the foil to curve its surface spatially. The arch is secured by screws to a steel block, which in turn is fixed to the inner side of the frame section. The lower web of the frame is connected to the steel substructure using standard bolts. This technique forms a single layered façade which protects the inside of the building from wind and rain. For this application heat or acoustical protection was not required, the intention was actually to create realistic outdoor conditions as far as possible. Supported by the Deutsche Bundesstiftung Umwelt (DBU), one of Europe’s largest foundations to promote innovative environmental projects, a research project in cooperation with Hightex GmbH and Herzogdesign® has started to develop these tensioned foil structures further. The aim is to extend the capacity of this technology towards multilayered, insulating and wide-span structures for extended roof and façade applications and to standardise these foil constructions for future usages.

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© Photo: Dr.-Ing. Gregor Grunwald

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<td>Structural engineers:</td>
<td>Sailer Stepan und Partner Beratende Ingenieure für Bauwesen GmbH, München</td>
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<td>Project Engineer:</td>
<td>Johannes Maier</td>
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**Failure of fabric reinforced membranes**

**A yarn based modelling approach**

**Introduction**

Fabric reinforced membranes are a class of lightweight materials which are important for many different engineering branches like civil, aeronautical or marine engineering. They can be used to efficiently cover large areas or enclose large volumes with a minimum of structural weight. Applications as membrane roofs, airship skins or sail materials demonstrate their capabilities. The vastly expanding numbers of architectural applications underline the aesthetic value of these types of lightweight structures. Constructed as a composite of a fabric embedded in or coated with matrix material, they combine the load carrying capabilities of fabrics with the functional tasks of the coating in order to obtain strong fluid- or gas-tight materials. Due to the microstructure of the fabrics, which consists of crossing groups of yarns, the macroscopic deformation and failure behaviour of fabric reinforced membranes differs strongly from the behaviour observed in common homogeneous membrane materials. The interactions of the yarn groups lead to a non-linear deformation behaviour like crimp interchange or shear locking and cause the discrete nature of the failure process, which is characterised by a successive or collective tearing of the single yarns.

The modelling approaches frequently used for the design and dimensioning of membrane structures do not or only partially consider these effects, as the numerical cost of the analyses would drastically increase. In addition a more detailed description of the material would require also a deeper knowledge of the material at hand, which is costly and impractical for realistic engineering applications underlying strict cost and time constraints. This lack of accuracy on the analysis side is usually counterbalanced by the experience of the engineers and the application of testing and a trial and error type of approach. Nevertheless, if confronted with cases in which failure occurs, in the civil engineering application usually in the erection and pre-stressing process, numerical models using the limited homogeneous material representation could not at all help further in explaining or avoiding the damage. The same need for high accuracy strength predictions is evident in aerospace applications in which the material capabilities must be fully exploited in order to allow minimum weight configurations. In this sense it is even more surprising, that modelling of failure in fabric reinforced membranes did gather only little attention in engineering science in the last decades. The present paper shows some of the results obtained in a PhD thesis which aimed at contributing to this topic. The thesis resulted from the authors work at the Institute of Static and Dynamic of Aerospace structures of the University of Stuttgart under the supervision of Prof. Dr.-Ing. habil. Bernd Kröplin[1].

**Yarn based modelling approach**

The fabric membranes are characterised by a microstructure of yarns, which are interwoven and embedded in a matrix material. Even if the focus of interest is laid only on the macroscopic response of this kind of material, as it is the case for engineering analyses of membrane constructions, the underlying structure of yarns have a dominating effect on the deformation behaviour. The well known macroscopic nonlinearities in the fabric deformation namely crimp interchange and shear locking, directly result from effects on the microstructure. The majority of the existing modelling approaches for fabric membranes cannot fully integrate this micro-structural influence in a simulation on structural level. The representation of the fabric as a continuum, as applied in finite element simulations, can include the nonlinear material behaviour stemming from the yarn structure, but its deformations and interactions are not considered. In addition it has to be concluded from theoretical studies on the unit cell of a fabric weave that the system response is in reality load path dependent and not in any case invertible. None of the common continuum type approaches will be able to reproduce this behaviour. Instead it could provocatively be stated, that a fabric should rather be treated as a structure than as a material.

Simplifications of continuum type material model approaches of course have their right to exist and will be the approach of choice for the majority of applications. Still it should be clear, that their accuracy and physical meaning is restricted and has to be treated with great care.

In the work presented here a different route to the modelling of fabric material behaviour is chosen. The starting point is the above statement, that fabrics should be treated as a structure. A discrete model for fabrics and fabric membranes is developed, which is based on the microstructure level of the yarns. The aim is not to prove the fundamental assumption, that the nonlinear deformation behaviour as well as the failure process is dominated by the yarns. It is also sought to explore, how far into the macroscopic world of real life structures this kind of bottom up modelling approach can be driven. The used abstract representation of the yarn structure applies the well-known and proven simplification of linearised yarn paths between the crossing points. A multitude of this generated unit cells - the smallest repeatable structure unit of the fabric - are assembled to build a macroscopic patch of fabric (Figure 1). In order to solve this system, an efficient numerical method is necessary, allowing for large deformations, damage and free movement. With the Discrete Element Method (DEM) an explicit particle based method is chosen, which is usually applied in granular material modelling or in damage simulations[1]. The result is a model for fabric membranes which allows a direct microstructure representation in simulations on a structural (macroscopic) level. The macroscopic nonlinearities that stem from the interactions of the yarns implicitly arise from the representation of the yarn structure without the need for further assumptions.

**Figure 1:** Model representation of fabric material: fabric patch – unit cell – model unit cell – assembled model fabric patch.
membranes.

Fabric Membrane model
The application of the Discrete Element Methods makes it necessary to discretize the mass of the fabric into point masses and to define interactions between these mass points which represent the mechanical behaviour of the constituents on this microscopic level. The yarns are discretized into point masses located at the crossing points of the yarns (Figure 2). Three interaction types define the deformation behaviour of the fabric: (A) longitudinal yarn stretching, (B) transverse yarn compression and (C) yarn rotation around the crossings. Two additional types of interactions, (D) matrix stretching and (E) matrix shearing, are applied in order to represent the coating of a fabric membrane. The simplifying assumption of piecewise linear yarn sections between the crossing points is a common approach for the description of fabric unit cell followed e.g. by Kawabata [9].

In the frame of this model a relative translational movement of the yarns at the crossings is inhibited (pin-joint-model), thus friction effects between the yarns are neglected. Detailed descriptions of the model development and the applied interactions can be found in [1, 4 and 5].

Deformation mechanisms
In the frame of the authors work [1, 4 and 5] experimental results for the deformation behaviour of different fabric membrane materials have been obtained, which span the range from a pure, uncoated fabric to a stiff fabric reinforced membrane. These results have been used to develop and verify the presented fabric membrane model. A procedure for the parameter identification based on tests has been formulated. As the focus of the present paper is the failure simulation, only one example for the nonlinear deformation behaviour is given here. More information can be obtained in the given references. Both typical non-linear fabric deformation mechanisms could be observed in the setup of the bias extension test.

On the one hand this test is basically a shear test, showing clearly the shear locking mechanism. In the centre of the long specimen a nearly pure shear region exists. If the shear limit is reached, the resistance against further elongation of the specimen increases and finally also a longitudinal wrinkle occurs. On the other hand, also regions of tension along the yarns are existent near the clamping of the specimen, which show the crimp interchange mechanism. Thus the bias extension test is a suitable setup for an overall reference case for the assessment of the model performance.

A bias extension test has been performed on a pure glass fabric and a glass fabric coated with silicon. Based on experimental results from uniaxial and biaxial tension test the geometric and tensional model parameters have been identified. The shear parameters are fitted with the results of the bias extension test. Figure 3 shows the comparison of the experimental and the simulation results. The deformation behaviour as well as the resistance response for the fabric and the membrane are represented well.

Failure modelling
The above stated results demonstrate the applicability and the relevance of the model for the deformation behaviour. Not only the macroscopic nonlinearities are captured, also the deformation and movement of the local microstructure, the individual yarns, are represented. Of course a detailed model on this scale will hardly be applied efficiently on structural scale. Its major application regime is the failure modelling. The failure is characterized by local interactions of the yarns as well as by macroscopic load redistribution mechanisms.

The derived fabric membrane model with direct yarn representation thus is predestined for the failure simulation, as both scales are captured well, and still, through the application of an efficient numerical solution technique, considerable parts of a structure can be simulated. The extension of the model for the failure simulation offers very interesting opportunities. As the yarn pieces between the crossing points are modelled individually, strength values can be assigned to each of them (Figure 4).

The solution technique allows the failure of single yarn pieces and the resulting load distribution and microstructure rearrangement is very close to the real fabric behaviour. In addition, statistical failure models can be applied. The strength values of the individual yarn pieces can take differing values. Their mean and standard deviation can be controlled, if a statistical distribution function is used for the assignment of strengths. In the presented model the two parameter Weibull distribution is chosen. The possibilities opened by this approach are demonstrated in the application examples.
Failure Simulation

In the damage process of fabric membranes two types of failure could be distinguished: Failure through rupture is defined by an abrupt and complete breaking of a previously undamaged sample. In the opposite, tearing failure is characterized by a gradually growing crack in a previously damaged material. Examples for both types are covered in the following.

Rupture strength

In the first example the rupture strength of a uniaxially loaded fabric patch is considered in a simulation with the fabric membrane model. The influence of the variance of the distribution of the strength values is explored in this setup. A patch of 40 x 40 yarns is modelled as rigidly clamped and uniaxially loaded along one yarn direction. As the individual strength values of the yarn pieces are randomly distributed (following a statistical distribution), a single simulation is not significant any more. A number of simulations have to be performed and statistically evaluated, in order to obtain meaningful results. In the given examples, six distribution functions are considered with five runs each. The results of the 30 runs plus one additional run with equal strength values for all yarn pieces are given in Figure 5.

An increasing spread of the strength values, which is realized by a reduction of the shape parameter $\alpha$ of the Weibull function parameter, leads to a considerable reduction of the strength of the patch. The failure process changes from a rupture type with one single continuous crack in the case of low spread to distributed cracking all over the patch in case of a high spread of yarn strength (Figure 6).

The failure regime in the latter case is larger, spanning over a considerable region of strain, while the maximum resistance is lower than in the abrupt rupture case. The spread of the individual strength values can be seen as an intrinsic material parameter and is characteristic for different material types. The distinction between a brittle and a more plastic type failure behaviour can be treated in this sense. The model allows the fitting of the distribution parameters to the assumed or experimentally obtained material characteristic.

Tearing strength

In the second example the tearing behaviour of fabric membranes with different coating stiffness is considered. A patch with an initial crack is loaded uniaxially perpendicular to the pre-crack and along one fibre direction. Variations in the initial crack length are applied, measured in terms of the crack length to width ratio (Figure 7). Four combinations of material parameters for the fabric are chosen in order to cover the range from the pure fabric over a soft and medium to a stiff membrane. The spread of the distribution function of the yarn strengths is fixed at a medium value of $\alpha=30$. As result the maximum resistance force of the patch is obtained. This value is divided by the number of initially load carrying yarns and made dimensionless with the strength of the undamaged reference patch of same material. The plot in Figure 7 summarizes the simulation results.

For the uncoated fabric, no influence of the crack is obtained. With increasing stiffness of the coating, the resulting strength value is reduced. The observed reduction is also dependent from the length of the crack, but nearly constant for crack lengths away from the limits of total or no initial slits. The result is in a certain sense surprising. An increasing stiffness of a coating reduces the efficiency of the load carrying capability of the fabric membrane under tearing conditions. The mechanism that is responsible for this effect can be explained with the applied model: The coating of the fabric leads to a transfer of load from the region behind the pre-crack into the remaining yarns through an increased shear stiffness. This leads to an additional overloading of the next yarn at the crack tip. This overload of the next yarn is even higher, the stiffer the coating gets.

In Figure 8 the loading situation prior to the first yarn failure is visualized for the four materials. The colour code represents the load of the individual yarns in relation to its load limit. It gets clear, that the coated patches show a stronger overload of the yarns at the crack tip and thus will result in a reduced utilization of yarn strength in a tearing situation.
Biaxial tearing

In this last application example the previous tearing setup is extended to a biaxial load situation. A now quadratic patch is clamped at all four sides and loaded along both yarn directions with strain control. The ratio between the applied external strains in the two directions is one, i.e. equal load is applied. An initial crack is introduced in the patch which is inclined at 45 degrees to the two yarn directions (Figure 9). The interesting aspect in this setup is the direction of crack growth and the pattern of the final cracking. In order to reduce complexity, only one material system representing a medium stiff fabric membrane is considered.

As a result of the simulation, the forces in the two directions are obtained. Figure 10 shows the force vs. the applied strain in the two directions warp and fill on the left. In the given example the fill yarns reach their failure levels first. They nearly completely fail before the cracking of the warp yarns starts. The visualizations of two sequential cracking states on the right side of Figure 10 depict the damage state after the failure of the fill yarns only (top) and at the end of the simulation run, when both yarn groups are broken (bottom). The order, in which the two groups break, is depending on the specific distributed strength values. In a second run with the same set of parameters but a different random collection of strength values, this situation might as well prefer the warp direction.

The loading situation in the patch is depicted in Figure 11. The strain of the individual yarns divided by their strain limit is colour coded for the warp yarns in the top and for the fill yarns in the bottom row. From left to right the figures show the situation before the first yarn failure, after complete failure of the fill yarns and after the final failure of the warp yarns. As in the case of the uniaxial tearing, the next yarn to the crack tip is overloaded in comparison to the yarns further away from the crack tip. It is noticeable, that the already fully developed crack in the fill direction has only a small influence on the strain situation in the second direction.

Thus two major observations could be made in this simulation:
1) The fabric membrane shows a clear tendency to break parallel to the yarn directions.
2) The two yarn directions break nearly independent from each other.

The first issue is an observation made also in experimental studies on the biaxial tearing of fabric membranes. The second observation is also depending on the stiffness of the coating. The more medium stiff fabric membranes are broken (bottom). The order, in which the two groups break, is depending on the specific distributed

REFERENCES

CONCLUSION
The obtained model makes use of the full capabilities of the approach with a direct microstructure representation. It enables an integration of the theoretical models for the statistical damage description into a simulation on a structural level. Furthermore it is capable to reproduce in a realistic manner the tearing and rupture process of the fabric membranes. The developed discrete model for fabric reinforced membranes allows the exploration of the interactions of the yarns and the influence of the coating materials in the simulation of experimental setups like the uniaxial or biaxial tearing. Its application can lead to a deeper understanding of the processes that characterise the failure of fabric membranes. The scale of considered problems is limited by the available computer power. Currently applications to patches of few hundred yarns per side have been demonstrated successfully.

Thus the model is ready for application on the level of test lab specimens. As additional final conclusion the uniqueness of the material behaviour of fabric membranes should be again pointed out. There exist only few other materials in which the microstructure length scale is as near to the macroscopic level as in the case of fabrics. The nonlinearities in the deformation behaviour and the specific failure mechanism are directly related to this close connection of structural length scales. All given results show clearly, that considerable care has to be taken in the choice of simplifications to apply in modelling approaches for this extremely interesting material class. In many cases the traditional engineering approaches basing on finite element simulation and continuum representations will not yield sufficient accuracy of analysis results.

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A pragmatic approach to determining the mechanical behaviour of structural fabrics.

INDUSTRY SUPPORTED PHD STARTED AT NEWCASTLE UNIVERSITY

In October 2008 work began on a new project in the school of Civil Engineering and Geosciences entitled ‘A pragmatic approach to determining the mechanical behaviour of structural fabrics.’ Alison Jackson, a Newcastle University Civil Engineering graduate with 2 years industry experience at Arup is supported by a supervisory team comprising Prof. Peter Gosling, Dr. Ben Bridgens and Prof. Jon Mills (photogeometry and measurement) to carry out the 3 year study. The project is backed by a consortium of industrial partners; Architen Landrell Associates, Arup, Buro Happold, Ferrari, Tensys and the UK Engineering and Physical Sciences Research Council. Newcastle University’s floating biaxial test frame (Figure 1) will be used in conjunction with a hinged frame shear accessory (Figure 2) in a new temperature controlled test facility (Figure 3) to obtain data on material behaviour under biaxial and shear loading. This data will be used to demonstrate the capabilities of a predictive numerical model developed within the project.

The aim of the research project is to develop a numerical tool to enable the reasonable prediction of structural fabrics. The unit cell model will then be extended to include shear response which will require the introduction of the concept of lock-up at angle as a function of biaxial stress ratio and magnitudes. Repeated concatenation of unit cells will be used to produce a “patch” of fabric (e.g. 300 – 400mm) required for shear behaviour prediction. The extended ‘patch’ model will then be used to predict the strength of the fabric under virgin and torn (e.g. 40mm tear in a 400mm wide patch) states by considering both stress and strain states.

The capabilities of the predictive model will be demonstrable by comparison with data acquired from a series of uniaxial, biaxial and shear tests. In order to run these tests a new protocol will be written for shear and failure testing of fabric based on the principles of the existing biaxial test protocol. This will enable full quantification of the fabric response to in-plane loads allowing extensive comparison between test data and predicted values. The variability in fabric strength and stiffness characteristics will be identified from physical testing and the ability of the numerical model to predict this will be demonstrated. In order to do this the variations in measured parameters will be input into the numeric model to predict the same measured variability of the parent fabric.

Finally the predictive model will be linked to the concept of info-gap theory and the application of the predictive tool to explore the uncertainties in the existing analysis of fabric structures. It is hoped that this will enable future design to maximise the robustness of the structure for a given performance (e.g. stress/deflection etc.) where knowledge of the variability of the fabric is incomplete. This will be achieved by consideration of only simple examples (pseudo manually) as an early proof of concept in preparation for full adoption of the tool in a future project.

The key hypothesis is that the non-linear stiffness and strength characteristics of coated and uncoated woven fabrics can be stated as an envelope of values. Complex performance can be predicted from simple information which is easily obtainable from a small sample of the material in question when referenced against a database of predicted and test responses. Whilst the predicted envelope of values may not be as accurate as that obtained from a full set of comprehensive tests it is expected that the predicted behaviour will be suitable for all the most demanding projects and better than any obtained by current biaxial testing.

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 ينبغي www.ceg.ncl.ac.uk

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Figure 1: Floating biaxial rig.
Figure 2: Hinged frame shear accessory.
Figure 3: The new temperature controlled test facility at Newcastle University.
Figure 4: Unit cell model developed by Bridgens.
Circular textile roofs usually end up as conoids with a central mast or suspended high point. Nevertheless, other solutions are possible provided that the perimeter is not included in the same plane. For the "Castle" Disco in Santa Pola a circular paraboloid was designed.

Description
The enclosure is circular in plan, 35m in diameter, including a central dance/stage floor, surrounded by a circular porch with tables, benches and seats. An intermediate space in-between provides either complementary seats or a central dance/stage floor extension. Main entrance, services, bar and other facilities complete the whole scheme (Figure 1).

Textile roofs
Textile roofs were envisaged for the central dance floor and the intermediate space. The central dance floor is roofed with a concave double curved surface, stretched against a spatial ring, 12m in diameter. The spatial ring is made of two leaning trussed arches supported by 6 masts that follow and reinforce the contour of the dance floor or stage (Figure 2). The intermediate space, 26m in diameter, runs between the arches and the porch. It is divided into two symmetrical parts by the drainage of the central roof. They are attached to the perimeter independently in such a way that either of both parts, only one or none can be installed for sun protection purposes. They complete the space directing the shape towards the centre, assisted by the seams resulting from the cutting pattern. Notice that the cutting pattern is not only a concern for making the form, but it also contributes significantly to the perception of the surface, in this case, directed towards the central dance or stage floor, emphasizing that something (or somebody) important is going to happen there.

Steel structure
The steel structure is also relevant. There are 4 single CHS masts and 2 three-fold CHS masts supporting the trussed arches. The porch is delimited by a series of 20 double CHS in order to be self-supporting and avoid ties between tables and seats (Figure 3).

Design concerns
The design of the aforementioned roof was used to reveal the difficulty of most 3D design programs to find in some circumstances the equilibrium form of a physical model of a tensile surface structure. The figures show the perimeter of the intermediate spaces, the surface generated by a 3D design programme (Figure 4), a physical model (Figure 5) and a computer form finding made with Easy Demo, Technet GmbH (Figure 6). Notice that the 3D design model is not in equilibrium and is not feasible.

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Tensile fabric structures offer possibilities for the solution of urban problems which no other type of structure permits. In the Expo Zaragoza 2008 site (Saragossa, Spain) a 400m long structure has been designed that has turned out to be one of leading attractions of the event. It consists of thirteen pieces of torical surfaces that twist and turn at a height of 17m, taking on the appearance of a river. Technically, it includes some advances in structural geometry and artistically, it stands out due to its formal decoration.

With the aim of providing shade for the participants’ street we build a partial roof along the 500m of its length in such a way that no element would interfere with the views from the pavilions to the street or obstruct the route where various activities would take place.

This commission would not have been a problem in itself if it were not for the fact that several limitations existed. We could not place anchorages on the existing buildings because they were not dimensioned for it or in the public walkway as activities which require the street to be obstacle-free were foreseen. The structural and architectural solutions had to be completely stable in themselves with respect to horizontal loading because the pavilions could only provide vertical reactions. These limitations strongly conditioned the final design, which was arrived at by two different paths. The first was conceptual, and consisted in providing the project with a symbolic image. The other was structural, via which we searched for possible forms which would resolve their stresses internally and would convert them exclusively into vertical loads.

The conceptual idea consisted of using the exhibition’s own leitmotiv, based on water, and building a river which flowed overhead and cast its shade onto the main street. Our objective was to represent Zaragoza’s river (Figure 1).

The structural idea was based on a self-stressed system which resolves all pre-stresses internally and only transmits to the exterior the actions of gravity, snow and wind loads. We thought that a modular design would help in solving all the problems and modules of 32m x 24m were proposed, with a central part of these comprising 14m x 32m of textile. To prevent the repetition of 13 of these modules from being monotonous, they were mounted in such a way that they curve, as though it were the meandering of a river bed (Figure 2).

In order to round off the idea, the textile roof is covered with artistic patterns, which we consider to be a plastic work which combines technique and design, as can be seen in the pictures of the finished project. We wanted the architectural image to be complemented with a design by one of the country’s most important artists, in this case Isidro Ferrer (Figure 3).

Our main challenge was to achieve a support for the textile fabric surfaces capable of functioning in a self-stress state, that is to say, with vertical reactions exclusively. The horizontal reactions typical of these kinds of structures and arches were avoided with a disposition as in Figure 4, where tubular metallic arches would be stabilised by tendons on the upper part of the arches and by cables below them. It is precisely the introduction of these upper tendons which has been special for this project, since an arch is considered to be stable when it cannot open by an outward horizontal thrust, and here the arch cannot expand because of the lower cable, but with respect of the action of the fabric we have also prevented it from closing inwards as it cannot increase its curvature due to the upper tendon. The lower cable works with pushing loads and the superior tendons work when pulling loads are acting.

A succession of fourteen arches set at 32m intervals leaves thirteen zones in which modular roofs can be drawn taut. The covers are designed to be seen and to be used as a continuous canopy over the street.
The tensile fabric structures used are surfaces of toric geometry (the inner part of a doughnut), 14m wide and 32m long, as mentioned above. The pieces used are limited by two vertical planes and two curves with circular projection.

In order to support the curved fabric borders we placed curved steel cable edges at the exterior, which are the fundamentals of the entire structure, as between the self-stressed arches and these border cables or “bolt ropes” (curved edge cables with bolts, see Figure 16) a highly resistant fabric is tensioned, which defines our overall design.

In order to complete it we dispose another series of cables and rods which are fundamental for the functioning of the assembly but which are barely visually perceptible.

The way the arches are supported along the axis is different on the right side. On the right, they are connected to the roof of the pavilion buildings while, on the left, they are connected to the top of 17m high masts and arches are rigidly connected, more to facilitate improved at the points where the walkways between pavilions are supported. On the roof, arches are supported directly on the post-tensioned concrete slab at the points where there is a concrete support directly below (Figure 9) or on a steel laminated rod to avoid encountering the heads of the tension cables of the concrete slabs (Figure 10). These supports are dimensioned to carry almost exclusively vertical loads and only some small occasional horizontal forces.

The arches tensioned on their lower side with a cable and on the upper side with a combination of sticks and tendons are constructed in a parabolic curve made with segments of 400mm x 200mm rectangular pipes where the tensile fabric, interior cables and edge cable devices are connected to. Because the street is not uniform in width not all of the arches are equal.

There are two types: arches with a 24m span and arches with a span of 32m, although all of them have the same height of 6m (Figure 11). In order to make the edges of the textile taut a succession of parallel cables was added and connected to a border comprising two parallel cables in a parabolic curve, resulting in a technological solution such as shown in Figure 12. Generally speaking, we try to make our designs completely stable in themselves, even when the textile elements are absent. In this way, even if a textile cloth had a structural defect this would not imply the collapse of the rigid elements.

Everything that has been said about a self-stressed system works for the interior modules, but not in all aspects for those at the beginning and the end of the street. This is because there are horizontal forces here that can only be absorbed by means of anchorages to fixed points with the transmission of important horizontal components. In order to solve this problem of equilibrium we ran inclined cables to fixed points on the foundations, as can be seen in Figure 13. We chose to connect at places where there were already other types of supports so as not to increase the number of obstacles in the street. On the other hand, as the loads from these cables are tension forces, the performance of the foundations is improved at the points where the walkways between pavilions are supported.

The role of the roof is not exclusively functional - providing shade - but it is also an important part of the functioning of the structure. When we installed the textile modules we achieved a total equilibrium of stresses where none of the elements is superfluous and each is indispensable. Nevertheless, certain considerations need to be taken into account with this kind of architecture in tension, and are worth emphasising as design principles:

1. Despite its high resistance under tension, the textile has very little resistance to tearing and rips can occur at the joints. When this happens stability is only lost between cables and the rest remains in place, and normally in good condition.

2. The textile meshes are designed in such a way that they maintain self-equilibrium when the textile is not in place, that is to say, that the
absence of textile does not imply either the fall of cables or the collapse of rigid elements.
3. These types of modular structures have to keep functioning even in the absence of a module, whether it is interior or exterior.
4. The stability of these structures is based on the fact that they are in a state of strong internal tension, which we refer to as pre-tension, before starting to introduce any exterior load.
5. The external loads, basically due to the wind, can act in a different way on each element at each moment in time.
6. The wind loads concentrate their energy in gusts and are thus dynamics of very long periods, between 0.5 and 2 seconds, which means that their movements are visible and therefore disturbing. The greater the initial pre-tension to stabilise the whole, the shorter will be the period of vibration.
7. The forms that can work for this type of roofs are warped. This means that they cannot be constructed from flat surfaces except with an adequate cutting pattern. In our case, we opted for a cutting pattern of a transverse type which takes full advantage of the commercial reel width.

All these aspects have been taken into consideration in the construction and structural composition of this roof.

Along with those already shown in previous figures, Figures 14 and 15 show the key aspects of the overall solution. Generally speaking, the construction details of this type of cover have been studied in depth and we have turned to previously-known solutions, although a certain degree of innovation is always necessary. Thus the “bolt ropes” (curved edge cables) are resolved with double cables in order to tighten the cables which of the arches are resolved bit by bit by means of a nut at each end (Figure 17).

Figure 17. Tension screws

One of the most important aspects of a textile roof project is to program the sequence of assembly and tensioning. In this case we chose to stress the entire metallic mesh previously, apart from the stressing which on each element at each moment in time.

Once the assembly is completed it is necessary to proceed to introduce tension into the fabric until achieving nominal design stress. This is difficult to check in the cables and even more so when it comes to the surfaces. The mechanised techniques which exist for this are not very trustworthy and it is better to operate by approximation on the basis of the reactions as, in the absence of external loads, the overall result suggests an equilibrium which is easy to check. The force applied via the screw threads at the extremes determine what happens in the interior in the absence of wind. For this reason, if we check the reactions of the few anchoring cables we have on the exterior we will be able to make an approximate estimation of what happens to the whole.

The analysis of this structure is really quite complicated due to its extension and owing to the nature of its components. Moreover, it is difficult to evaluate the loads and the simultaneity of their action. It is for this reason that we have made separate calculations for the textile elements and the metallic ones. In this way, the surfaces, along with their edge elements, have been analysed using the SAP2000 programme in order to obtain some generic stresses. The supporting elements, meanwhile, have been dimensioned with these previous reactions in order to obtain some stresses and reactions which have served to dimension the entire structure. Without entering into further detail, the loads which have been taken into consideration are wind loads when the wind is blowing at 100 km/h, and snow has not been taken into consideration as this roof will only be used during the three months that Expo 2008 lasts.

Posterior to the construction, wind speeds of up to 90 km/h have been measured without appreciating any alterations in the structure, which has served as confirmation that it is an appropriate and successful design.

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REFERENCES
Escrig, F. Sánchez, J. and Llorens, J.I. STAR Structural Architecture no. 5 and 6, Universidad de Sevilla, 1996 (star@us.es). ISSN 1137-201X

Name of the project: Textile roof over the street of participants in the Expo 2008 Zaragoza
Location address: Zaragoza
Client (investor): Sociedad Estatal EXPO2008
Function of building: to shadowing a public space
Type of application of the membrane: Roofs and Canopies
Year of construction: 2008
Architects: Félix Escrig and José Sánchez
Graphics: Isidro Ferrer
Multi disciplinary engineering: Performance S.L.
Structural engineers: Performance S.L.
Consulting engineer for the membrane: Performance S.L.
Engineering of the controlling mechanism: Performance S.L.
Main contractor: IASO S.A.
Contractor for the membrane: IASO S.A.
Supplier of the membrane material: Ferrari
Manufacture and installation: IASO S.A.
Material: FERRARI REF. 392
Covered surface: 5000m²
The new Rhine-Neckar-Arena in Sinsheim has been recently completely finished. A stand roofing system made of technical textiles round off the newly built stadium and offers protection for more than 30,000 spectators. CENO TEC GmbH, an enterprise from Greven-Germany, produced and installed the roofing system within only a few months.

**High-tech materials for functional use**

A total area of 19.500m² is covered by technical textiles. The amount of material used is around 60.000m². For optical and acoustic reasons not only the upper side, but also the lower side of the steel supporting structure is covered with the membranes. Two different membranes were used, depending on the function. The upper membrane that faces the outside is intended to protect against the weather whilst at the same time allowing light through onto the stands. 56 roof fields, each with 5 support arches, are covered with architectural membranes made of translucent PVC-coated polyester fabric (type III) having a dirt-repellent fluoropolymer coating. This varnish is more weathering resistant than traditional varnishes. The lower membrane that faces the stands is intended to have an optically calming effect. A fine-meshed PVC-coated polyester screen fabric is used for this. A total of 750 steel frames are finished with semi-transparent material. Another special feature of the roofing system is the fact that the 750 covered steel frames were produced in accordance with a joint model such that they can be displaced in order to achieve a closed homogenous ceiling.

The architect’s design has been consequently implemented with many technical individual solutions. The roof edge glazing planned for the inside of the stadium is also part of CENO TEC’s scope of delivery. Around 6.000m² of polycarbonate panelling will provide for protection against the weather and translucence around the entire circumference of the playing field.

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**Floating Roof**

New Rhine-Neckar-Arena, Sinsheim, Germany
3 AWARDS FOR FABRITEC STRUCTURES

FabriTec Structures garnered three awards in the 2008 International Achievement Award (IAA) competition presented by the Industrial Fabrics Association International (IFAI) for its exceptional specialty fabric projects. FabriTec won Outstanding Achievement awards for Grier Pavilion (Figure 1); a dazzling outdoor pavilion located on the top floor of the Riverside, California City Hall and for their Holiday Inn Palm Springs project (Figure 2); a high tech entryway structure which has become a unique focal point for the local landscape. The company also earned an Award of Excellence for their Santa Fe Opera House project (Figure 3). The custom tensile structure covers an outdoor eating and lecture area and is a visually stunning addition to the beloved Opera House. For 61 years, the International Achievement Awards have recognized skilful design, technological innovation and excellence in the specialty fabrics industry. FabriTec Structures has won several IAA awards in past years and is one of the five brands of USA SHADE & Fabric Structures, Inc. The company has experienced professionals in specialty construction and handles every aspect of the job including 3D/CAD Design & Concept Development, Engineering, Steel and Fabric Fabrication, Manufacturing, Project Management and Construction.

EAT STREET WESTFIELD LONDON NORTH WEST BUS INTERCHANGE

Architen Landrell has in October 2008 completed the design, manufacture and installation of largest Tenara structure in the UK for the opening of the Westfield London Shopping Centre. Working closely with the Westfield designers and construction professionals, Architen Landrell were contracted to create a 16 bay fabric canopy to cover and protect the ‘Eat Street’ area of the new WSL white city project. The area, which houses the main restaurants, cafes and bars on the site, is one of the busiest streets within the complex and therefore it was important to the designers to provide weather protection but also to keep the light and open air feeling. With Architen Landrell’s guidance, the team chose to use Gore Tenara, a PTFE based fabric which offers 30% or 40% light transmission, and at 160m long it is the largest Tenara structure in the UK! The canopy itself is split into three sections and is fixed three stories up, cantilevering off the main building. Due to the compressed programme towards the end of the Westfield 6 year build, the street became excessively busy with other contractors. As a result, we chose to perform the whole installation at night with multiple cranes and cherry pickers over a period of 2 months. Working nights also helped with access issues caused by the narrowness of the street itself. Cherry pickers and scissor lifts were adopted to take up minimal space but to speed up the installation process. The tight deadline was a real challenge for the team and required hard work, dedication and attentive project management. However, the work was completed and the shopping centre opened on time to the delight of all involved!