Dear Reader,

One of the objectives of TensiNet is to centralize information on tensile architecture and to make information available to all who is interested in this building technology. From now on it is possible to enter projects in the database through the website www.tensinet.com.

The partners of TensiNet have full access to the data. For all other architects, engineers, contractors, material suppliers, involved companies or building owners the procedure is to contact Jürgen Haase (jhaase@vub.ac.be) or myself (Marijke.Mollaert@vub.ac.be) to obtain an account and password to be able to add your project. The person introducing a project is responsible for the correctness of the information and will be mentioned as the owner of the data. The TensiNet database is not a commercial initiative. The data has to provide insight in the building technology and possibilities. For that reason we kindly invite you to add a description of the concept, to explain the arguments for a specific solution, to provide pictures and drawings and to give your comments.

We hope that this database becomes an important source of valuable expertise.

Marijke Mollaert
Building Principles of Tensegrity Structures

The tensegrity structures R. Buckminster Fuller and Kenneth Snelson started with are so called twist units. These units are made of two regular polygons opposite to each other, the edges are tension elements and the polygons are connected at the corners with compression and tension elements. The polygons are rotated against each other and causes the pretension forces in the upper and lower polygon as well as in the connecting diagonals, see Figure 1.

The equilibrium between tension and compression under pretension is closely related to the geometry of the twist units. By rotating the polygons against each other there exists only one position in which the tension elements connecting the polygons have the minimal length. In that position the tension elements can be pretensioned and a stable equilibrium is reached. By rotation over this position the tension elements have to be strained.

These simple tensegrity structures can be added to linear, two dimensional or double curved spaces structures. The following methods of assembling the twist units are existing:

- connecting the units in-between the tension elements of the polygons
- connecting the edges of the polygons
- connecting of the compression elements

The only possibility to get structures with disconnected compression elements is to add the twist unit while connecting them in-between the tension elements of the polygons. The result is a mesh of tension elements made by triangles of two sizes in the upper and lower layer. The tensioned meshes are connected by compression members and nearly vertical cables, figure 2a. The structure can be built by clamping the edges of one unit onto the polygon cable of the next unit. The addition of the twist units along their edges leads to connected compression elements, figure 2b, resulting in disconnected tensioned triangles in the upper and lower layer. Additional cables are necessary to connect the polygons. In this case the compression element of neighbouring twist units are parallel. By merging the parallel compression elements a double layer space truss is obtained with tension members, figure 2c.

A comparison of the three different types has been carried out. The pretension forces are assumed such that no cable gets slack under a uniformly distributed load of 2.5 kN/m² in the upper and lower layer. Results are an increasing stiffness form structure 2a to structures 2c and an increasing change of compression forces in the struts. The change of tension forces in the upper and lower layer is for all structures nearly the same. To be used as a three-dimensional space structure the system made of single twist units and disconnected compression elements (pure tensegrity structures defined by Richard Buckminster Fuller) causes, under a uniform distributed load, more weight and larger deflection than the systems with connected compression elements. Therefore not all of Richard Buckminster Fuller tensegrity systems are light and efficient structures, which can be confirmed by a more detailed examination of these structures and comparison with other structures.

Rosemarie Wagner
R.Wagner@fhm.edu

3DL for the New York Fashion Week

The following project for the 3DL exhibition hall was designed for the Fashion Week in New York’s Bryant Park. The architectural design of stainless steel structure had to meet following specifications:

- design as public relation
- temporary structure
- no fitted in the ground
- transportable

The form finding of the membrane led to an extraordinary result: a symmetrical air-supported structure (the building is stabilized by the uniform loading of pressure differential) with a specially designed surface. Within the form finding all main possible cutting pattern layouts were studied but unfortunately from the point of design, the seams did not meet the smoothness. Dreaming of a shape without cutting pattern the research went straight on to sailing technology. But there are only few technologies that allow a seamless production.

1988 J. P. Baudet and L. Dubois introduced a molding technology that allowed the first three dimensional lamination

© North Sails
Evaluation Method for the Elastic Moduli

1. Determination of linear elastic moduli: Theory

Before explaining the evaluation method we have to state the nomenclature: The index 1 indicates the warp direction, the index 2 the fill or weft direction. Stresses and strains have two indices since they are tensors of second rank.

E-moduli have four indices since they are tensors of fourth rank. Stresses are indicated by \( \sigma \), strains by \( \varepsilon \) and E-Moduli by \( E \). \( n_{11} \) means stress in warp direction, \( n_{22} \) stress in weft direction, \( e_{11} \) strain in warp direction, \( e_{22} \) strain in weft direction.

So we find the following relations:

\[
E_{1111} \text{ stiffness in warp direction}, \quad E_{2222} \text{ stiffness in weft direction}, \quad E_{1122} \text{ stiffness interaction between warp and weft}, \quad \varepsilon_{12} = \frac{E_{1122}}{E_{1111}} \text{ Poisson’s ratio for the interaction between warp and weft,} \quad \varepsilon_{21} = \frac{E_{2122}}{E_{2222}} \text{ Poisson’s ratio for the interaction between weft and warp.}
\]

In linear approximation we have the following relations:

\[
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22}
\end{bmatrix} = \begin{bmatrix}
E_{1111} & E_{1122} \\
E_{1212} & E_{2222}
\end{bmatrix} \begin{bmatrix}
\sigma_{11} \\
\sigma_{22}
\end{bmatrix}
\]

or, explicitly:

\[
\begin{align*}
n_{11} & = E_{1111} \varepsilon_{11} + E_{1122} \varepsilon_{22} \\
n_{22} & = E_{2122} \varepsilon_{11} + E_{2222} \varepsilon_{22}
\end{align*}
\]

It is to note that in general there are three moduli \( E_{1111} \), \( E_{1122} \) and \( E_{2222} \). We would like to add that one has to replace the stresses \( n \) and the deformations \( \varepsilon \) by \( \Delta n \) and \( \Delta \varepsilon \) if one wants to linearize a nonlinear behaviour in an interesting interval.

The interesting interval in a prestressed material is normally the interval between the prestress and the working stress.

2. Evaluation method

First it shall be mentioned that we are calculating the elastic moduli between an assumed prestress and probable working loads as shown in the load history, diagram 1. The procedure corresponds to a typical loading by wind followed by a loading by snow.

The evaluation method is explained in detail in the following diagram 2 which is extracted from a diagram containing the measured strains.

In the first part, the first three (or five) cycles of the load history, we have \( \Delta n_{11} = 0 \), \( \Delta n_{22} = 0 \).

The analogous strain values \( \Delta e_{11} \) and \( \Delta e_{22} \) can be read from the results.

In the second part we have \( \Delta n_{11} = 0 \), \( \Delta n_{22} \neq 0 \).

The analogous strain values \( \Delta e_{11} \) and \( \Delta e_{22} \) can be read from the results.

With these equations the moduli \( E_{1111} \), \( E_{1122} \) and \( E_{2222} \) can be calculated.

This procedure will be repeated for every part of the load history. Thus we can get an impression of the elastic moduli over the range of loading.

Rainer Blum
UFO - Microsoft

The introduction of Microsoft XT - introduced on the Czech market was connected with creation of the UFO hall. Air supported structure - symbolizing UFO - was made up of main ship and two additional semispheres. The fabric part was made by REKLAMA KUBICEK spol. s r.o., Brno (CZ). The complete structure was made up (for easier manipulation) from 9 separately sections with the possibility of interconnection. The structure was designed as double wall with wall thickness being 0,5 – 1,1 m. The windows were made out of transparent PVC foil. The stability of the constructions was ensured through permanent operation of 8 fans with pressure 0,6 kPa. Interior of the hall was done in white, yellow and red fabrics. The whole object was constructed with sawing machine technology. The entry tunnels in to the exposition were flat with no barriers.

Name: Pavilion UFO for the new SW - XT Microsoft
Location: Exhibition Invex, Brno 2001, Czech Republic
Name of final client: Microsoft CZ
Year of Construction: 2001
Planning period: 14 days
Handling period: 35 days
Design Construction: Katerina Vincourová, Prague, Berlin (CZ, D)
Structural engineer: Jaroslav Blanka, Michal Skalicky Ph.D. (CZ)
Supplier of the membrane structure: Aliachem a.s.
Material: PVC-coated polyester fabric
Covered area: 200 m²

Are All Membrane Structures Similar?

INTRODUCTION
To the untrained eye, all membrane and fabric structures look similar; they are white in colour and have curved surfaces. Some may think that, since the fabric material is thin and lightweight, it cannot be difficult to use for construction. If all this is true, why do architects and engineers talk about membrane and fabric structures in length and in such great detail? Markus Balz, Senior Engineer with Buro Happold, describes the challenges within the design and construction of the Top Golf clubhouse in Watford, UK in 2000.

TOPGOLF WATFORD, UK
Landrell Fabric Engineering appointed Buro Happold to undertake the conceptual design, structural analysis, detailed design and patterning for the Top Golf clubhouse in Watford. The building shape originated from some sketches by S & P Architects. The design also required the membrane to be supported by masts and for the membrane roof to have a partially glazed area to comply with daylight requirements. It was especially challenging to provide glazed areas within the membrane surface as membrane structures are deflection sensitive. Similar shaped structures to that required at Top Golf had been built before, with the lenses built as heavy bending elements, carrying the high tensile forces induced by the membrane to a few support cables. Furthermore, visually disturbing cables were used to deal with the uplift forces on the lenses under wind suction caused by the lack of curvature in the membrane shape.

The specific challenge on the Top Golf project was to prevent the use of interior cables and to minimise member sizes of the lenses. A solution was found by pre-stressing the lenses down against a series of thin hanger cables to the perimeter struts. Up to 200 kN of pre-stress force minimised deflections and bending moments in the long (up to 40m) slender lenses (Figure 2). At the same time the pre-stressed lens resisted the wind uplift, which frees the interior space of tie-down cables (Figure 1).

Figure 2 Lens pre-tensioned against perimeter structure

1st National Symposium on Tension Structures in São Paolo
Brazil, 6.-7. May 2002

The faculty of Architecture at the Escola Politécnica of São Paulo University organized the ‘1. Simposio Nacional sobre Tenso Estruturas’ in Brazil. The organization committee was led by the architect Jesse Salgado (Brasilasser) and chaired by the engineer Prof. Dr. Ruy Marcelo de Oliveira Pauletii. The symposium was attended by 500 participants, 50% of them were students. Frei Otto and his former students/collaborators were invited to give the keynote lectures. At first Frei Otto presented parts of his impressive work emphasizing on recent projects and was celebrated enthusiastically.

Prof. Balthasar Novak from Stuttgart, Germany, spoke about new developments on materials (i.e. Kevlar, Aramid, Carbon fibres etc.) and applications for ropes and membranes. These fibres are also qualified to strengthen existing structures such as the...
Fort 4 in Mortsel

Fort 4 in Mortsel was initially a military building. It has an internal court, which has a rectangular part and a wider round end. The rectangular part of the inner court is about 12m x 55m. The circular part has a radius of about 12m and an opening angle of 140°. The surrounding brick walls are about 12m high. The building is classified as a monument.

The membrane roof was designed for the summer season to provide shelter for cultural open-air events. Since the roof will be set up and demounted regularly with a limited crew and without cranes, the setting up procedure and handling was studied to be simple and fast.

The tensile roof for Fort 4 unifies functional (weather protection) as well as artistic aspects. The shape reminds of vaults in gothic cathedrals. The light roof is interacting with the massive walls by means of convex and concave arches. The alternate change of the height of the anchoring points is forming the arches. In the statical analysis only a medium upward wind load (since the surrounding walls protect the roof) and a minor wind pressure was verified. A PVC-coated polyester fabric of about 750g/m² has been used, reinforced with stainless steel AISI316 cables. Up to now the structure did behave quite well, even under strong winds.

The cultural events at Fort 4 are very successful, acoustic performances are high, light quality (in combining transparent and translucent materials) as well as the out-door feeling are pleasing. The interplay of functional and artistic properties improves the architectural perception in this place.

The installation procedure was carried out in 10 hours. Pre-installed masts lifted the lenses, with membrane attached, off the ground. No cranes were used, so to enable this lifting procedure, the installation process was analysed computationally and the lifting equipment was force controlled to minimise bending moments in the not yet stabilised long and slender lenses. Surveying the connection points prior to installation eliminated the need for many adjustment devices on the cables. Further savings were made by pre-stressing the whole membrane structure and the lenses in one go using hydraulic jacks pushing up to 28 tonnes into telescopic adjustable perimeter struts.

Architect: S & P Architects
Structural engineer: Buro Happold
Specialist contractor: Landrell Fabric Engineering
Year of construction: 2000
Covered surface (m²): 1500
Overall length in x-direction (m): 45
Overall length in y-direction (m): 35
Material: PVC coated polyester fabric (Ferrari 1502 PVDF)

CONCLUSION

The design of membrane structures always provides engineers and architects with new challenges in the design process. While the engineering of these structures is now well understood and all tools are set to provide accurate answers, new tasks in the development of shapes and structures can be undertaken adapting the first principles of the early pioneers. The true integration of all disciplines into a single ‘total’ solution is now also well-developed. Advanced modelling packages allow us to fully co-ordinate many aspects of a particular solution in detail before building. This enables us to provide glazed areas within a membrane surface without using heavy, framed elements to minimise deflection. This “game of forces and deflections” was demonstrated on the slender lenses of the Top Golf clubhouse.

Wolfgang Walochnik

From left: Jonas F. Salgado, Frei Otto, Jesse Salgado, Marcos L. Nuneles (Dupont do Brazil)
Ashford Designer Outlet Centre

Markus Balz, Senior Engineer with Buro Happold describes the engineering design, analysis & installation of the tensile fabric and cable structure that forms the roof of the Designer Outlet Centre in Ashford, UK.

Buro Happold was approached by the architects, Richard Rogers Partnership, to join a team to undertake the design of an out-of-town retail park in Ashford. In many ways this project was similar to earlier UK retail parks, with a tight budget and construction schedule. However, the project also presented further challenges in its planning and design, due to its location and the associated requirements of local planners.

The recent publication by the Lord Rogers-led UK Urban Task Force, ‘Towards an Urban Renaissance’, targets the re-use of brownfield sites for future development. The disused railway goods yard site purchased for this project presented the team with an ideal opportunity to push forward this important message. However, it brought with it planning criteria that reflected the prominent location of the site, on the edge of the Kent countryside. These planning criteria had to be met, but at the same time, the client brief demanded an iconic solution that would have presence when viewed from any of the surrounding roads or railway lines, acting as an advertisement in its own right.

With so many criteria and such a tight budget, the team decided to develop a tensile roof solution to cover and conceal the retail units below. The more malleable surfaces offered by fabrics allowed the team to look at solutions where the roof was seen to literally blend into the landscaping. At the same time, an iconic aesthetic would be generated through design options involving masted support systems with vertical drama. The final scheme was based on a horseshoe plan, with retail units looking inward to a ‘dished down’ car park, concealed from the rear by a sculpted tensile fabric and cable roof system.

Figure 1 shows the important relationship developed between the landscaping of a reinforced earth berm to the rear of the building and the surface of the roof concealing the retail units below.

A service road runs around the perimeter of the building, hidden behind the earth berm, with a continuous shopping promenade running around the inside of the retail units, protected by the inner ‘lip’ of the fabric surface and accessed from the central car park. A plan is shown as figure 2. The total area of the fabric and cable roof system is 35,000 sq.m, formed from a horseshoe of total length of 1000 metres. It encloses a total of 40 retail units of different sizes, all back-of-house facilities and a large clear span food court located on the primary axis of the development.

ROOF SUPERSTRUCTURE
The roof is set out on a series of radial grids spaced at 7.5m at the line of the front mast base. Radially oriented ridge and valley cables define a tensile fabric surface and lie on these radial grid lines. Ridges are picked up from a hanging system supported off a series of 24 tapered, tubular steelwork masts. The masts are 23m tall and are located at

Client: BAA McArthur Glen UK Ltd
Architect: Richard Rogers Partnership
Structural engineer: Buro Happold
Specialist contractor: Landrell Fabric Engineering
Main contractor: Galliford Northern
Steelwork contractor: Westbury Tubular Structures Ltd
Year of construction: 1996-2000
Covered surface (m²): 35000
Overall length in x-direction (m): 500
Overall length in y-direction (m): 200
Maximum height (m): 24
Material: PVC coated polyester fabric (Type III)

Inland Revenue Centre, Castle Meadow, Nottingham

The Inland Revenue headquarters shows how large scale office developments can reclaim a derelict industrial site for city centre uses and provide comfortable workplaces with low running costs. When Hopkins won the Inland Revenue competition in 1992, the budget, timescale and even the piles for a previous scheme were all in place. Hopkins’ design offered a new vision of a workplace for 1800 people, using the advantages of its canalside site, proximity to the city centre and the client’s commitment to an open, welcoming and efficient office complex which would transform the image and operation of the

Name of the project: Inland Revenue Centre, Nottingham
Location address: Castle Meadow Road, Nottingham, England
Name of the client / building owner: Inland Revenue
Year of Construction: 1992 - 1995
Architect: Michael Hopkins and Partners
Structural engineers: Ove Arup and Partners
Contractor for the membrane structure: Koch Hi-Tex
Supplier of the membrane material: Verseidag
Material: PTFE coated glass fabric
Covered surface: 2000 m²
Inland Revenue, and re-connect the derelict industrial site with the city. Proposing several buildings within a network of tree-lined avenues around a central spine brought several benefits. It introduced public access; 400 car parking spaces could be spread across the site; it suited the Revenue’s group-based operations; and its layout could centre on the amenity block rather than a boardroom or chief executive’s office. Its sail-shaped fabric roof billows and its masts soar amid its brick and lead neighbours to proclaim its special functions: a sports hall, bar, restaurant and nursery for 50 children enjoy its light, airy atmosphere and views towards the castle. Pre-fabricating the brick piers and the undulating concrete vaults brought higher quality and saved time over conventional techniques. The result also brings quality to the workplace, making column-free space and assisting passive environmental control. It was the first British project to receive maximum points under the BREEAM assessment; confirming its status as cost effective, an enhancement to its city and a model for re-using derelict sites.

Sub-models were stitched together by ‘transitions’, 15m wide zones of structure across which the cutting patterns were blended from one standard type into the next adjacent type. Equilibrium of force across these transitions was checked and maintained, ensuring that the sub-models were correctly connected and that modelling assumptions were supported.

With so many of the structural forces contained within the closed rings of the ridge hanger cables and the surface membrane, the entire system had to be checked for disproportionate collapse, to ensure that the canopy remains stable in the event of a mast or cable failure. This was checked by creating an elongated analysis model that simulated approximately 40% of the overall structure, see figure 4. The worst temporary wind load case forced the affected mast approximately 1m out of position, but ring forces were transferred through the mast tie-backs to ground.

Similarly, membrane stresses in the type III PVC coated polyester fabric are carried through the surface from one panel to the next in a second closed tension ring, equilibrating forces within the superstructure and minimising the requirement for large ground anchorages. The membrane is pulled out at the front by a cable tie-down and is restrained at the rear by a steelwork tripod.

**FORM FINDING, ANALYSIS AND DESIGN**

The early form of the membrane surface for the Outlet Centre was defined from the planning requirements, but was optimised for efficiency. The membrane stresses were equal (as in ‘soap bubble’ or minimum surface) over the majority of the fabric (150 kg/m warp and fill tensions), with ‘necking in’ effects around the ridge suspension points minimised through a locally varying stress field. All computer-aided design work was completed on the Tensyl software suite, a Buro Happold in-house membrane analysis package.

The structure was analysed as five sub-models with each analysis sub-model beginning and ending on a grid-line located plane of restraint or mirror line. Each sub-model was analysed for between four to six load cases of wind, snow and combinations of the two.

45m centres where they support the mast line ridge cables. The two intermediate cable ridges are supported off a ridge hanger cable. Figure 3 shows an isometric on layout of the roof structure layout.

The Ø52mm (increasing to Ø56mm) ridge hanger cable runs around the full length of the roof, ensuring force flow is optimised and self-contained. Although the masts are guyed at each location, the minimum of force is taken to ground here. This ‘washing line’ is nearly 1km in length and carries up to 800kN of force.

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School of Architecture of Barcelona
Universitat Politècnica de Catalunya - Spain

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- Total quality in the building process
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- Conditioning, energy and services

Prof. Josep Llorens

The Department acts as researcher, consultant or collaborator in reports, projects and building operations. The staff belong to standard committees and write articles, monographs and contribute to several publications, participating in national and international symposiums and conferences.

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Detail database: http://www.upc.es/ca1/cat/recerca/tensilestruc/portada.html

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