Chapter 2
The Design, Analysis and Construction of Tensile Fabric Structures

Abstract Coated fabrics and foils, used for architectural applications, are presented in the first part of this chapter. The current fibres and coatings available on the market are described in detail according to their performance, the advantages/disadvantages and current applications in architecture. The second part is focused on the most common typologies of tension structures, the design process and the comparison with conventional roofing forms. The main physical and digital techniques for form-finding, static and dynamic analysis, patterning and manufacturing are described in detail.

Keywords Coated fabrics · Foils · PVC · PTFE · ETFE · Form-finding · Force density · Dynamic relaxation · Patterning

2.1 Architectural Fabric and Foils

In membrane structures three main type of material are generally used: coated fabrics, open mesh fabrics and foils.

Coated fabrics present a symmetrical structure of yarns arranged in two main orthogonal directions: warp and fill. The yarns consist of threads parallel or twisted together and can be made of several materials. While the structural function is mainly provided by the yarns, the protection from chemical and biological influences, fire-retardant behaviour, weld ability, waterproof qualities and UV ray resistance depend on the coating layer.

For applications which do not require weather tightness, the use of open mesh fabrics is recently becoming quite popular. The weaving pattern can be designed in order to achieve the required level of solar protection and the design can take advantage of the reduced wind loads and of the substantial absence of ponding and wrinkles due to the permeable structure.

P. Beccarelli, *Biaxial Testing for Fabrics and Foils*,
PoliMI SpringerBriefs, DOI 10.1007/978-3-319-02228-4_2

Architectural foils are widely used for pneumatic application thanks to their level of air tightness, however, the reduced mechanical properties limit their use for large cushions and single skin envelopes. In recent projects, this limit has been partially addressed by adding reinforcing steel cables as a support in case of heavy loads.

2.1.1 Fibres

The term ‘technical fabric’ is used to indicate the wide class of fabrics in which the technical aspects are more significant than the aesthetic ones. The material of the fibres is one of the most important factors which contribute to the final performance of the fabric, especially from the mechanical point of view.

The fibres can be natural or artificial. The natural fibres have the considerable advantage of a reduced environmental impact, however, their properties cannot be significantly changed in order to meet particular requirements and this reduces considerably their application. Whereas artificial fibres can be obtained by using a wide range of bulk materials and processes which satisfy a wide range of requirements such as the mechanical and chemical properties. The fibres are expressly designed in order to satisfy specific requirements due to their final application, and can be obtained as an improvement upon existing commercial fibres, through particular processes and treatments, or created for specific high demand industrial applications (Corazza 2006).

The most common synthetic fibres are acrylic, aramid (commercialised as Twaron, Kevlar, Technora and Nomex), carbon (commercialised as Tenax), derclon, microfiber, modacrylic, nylon, olefin, polyester, polyethylene (commercialised as Dyneema and Spectra), spandex, vinalon and zylon.

The production of architectural fabrics is mostly focused on polyester (PES), polyethylene (PE) and fiberglass (Goldsmith 2013). Expanded polytetrafluoroethylene (PTFE), generally used in the coating layer, is now also available for yarns for specific applications (lighting, sound absorption, easy recycling, etc.). Finally, for indoor and temporary applications, other fibres like elastane and nylon are used.

2.1.1.1 Polyester

The most used fibre for architectural fabrics since the early 1960s due to the reduced price, good mechanical performance and the expected lifespan. The progressive degradation due to UV rays and the behaviour in case of fire can be easily improved with an adequate coating. The fibres are quite flexible and are very common for temporary and seasonal structures. Thanks to new technologies, coated fabrics, based on polyester fibres, are now recyclable.

2.1.1.2 Polyethylene

Polyethylene fabrics are generally woven from high-density polyethylene slit tape and coated on both sides. It is generally used for low-budget applications despite the shorter life span compared to polyester. Knitted fabrics for shading applications are one of the recent and most promising uses of high-density polyethylene in architecture. The fire behaviour and the resistance to UV rays can be improved through the use of specific additives.

2.1.1.3 Fiberglass

Glass fibres are generally used for permanent heavy duty applications due to the high modulus of elasticity and the tensile strength, and because of its intrinsic high resistance to fire and UV degradation it does not require additional additives. However, glass fibres are quite brittle and can crack easily and for this reason the panels of fabric should be folded and handled with care avoiding repeated flexing and low radius of curvature.

2.1.1.4 Expanded PTFE

Architectural fabrics based on Expanded PTFE are relatively new and commonly used for seasonal and deployable structures due to the high translucency, strength, flexibility, long life-span, high chemical resistance and very good soiling behaviour. Due to the high costs this material is generally used for specific projects which require, and highlight, its unique luminosity.

2.1.1.5 Nylon

Nylon fibres are generally used for projects and products which require lightweight and stretchable fabrics with relatively low mechanical properties. Thus, they are commonly used for small temporary and deployable structures both for indoor and outdoor applications.

2.1.1.6 Aramids

These fibres are very popular for nautical applications due to the extremely high modulus of elasticity and breaking strength. They are non-combustible but need to be protected against UV light. In architecture, due to the relative high price, their use is generally related to special applications which require their unique mechanical performance.

2.1.1.7 Acrylic

Acrylic fibres are synthetic fibres extensively used for furnishing fabrics. In architecture, due to the reduced mechanical performance, they are used for small deployable tents and umbrellas due to their flexibility and good resistance to oils, chemicals, and to deterioration from sunlight exposure. In addition, it can also be made to mimic other fibres such as cotton.

2.1.1.8 Polyurethane

Elastane, a polyurethane-polyurea copolymer, is exclusively used for indoor applications which require exceptional elasticity. Highly appreciated for the relatively low price and the reduced risk of wrinkles, this type of fabric is not suitable for wind and snow loads.

2.1.1.9 Cotton

Pure cotton is characterised by a poor tensile strength, a relatively high elasticity and a high vulnerability to microbial attack and the consequent biological degradation. For this reason its use is mainly restricted to leisure tents, indoor applications and projects which do not requires high and durable mechanical performance (Stegmaier et al. 2010).

2.1.2 Coatings

The final properties of a coated fabric, with the only exception of the mechanical performance, are mainly related to the materials used for the top coatings. They are usually placed on both sides of the fabric and can be combined with several additives in order to achieve the requirements in terms of weather and UV resistance, chemical and biological attacks, fire behaviour and colour stability. Therefore, the quality of the coating is fundamental for the service life of the material.

The doctor blade (PVC) and the dip coating (PTFE) are the most common coating methods however, the coatings can be applied to the fabric also by laminating, rolling or brushing on the basis of the chemical compatibility with the fibres.

2.1.2.1 PVC

Polyvinylchloride (PVC) is generally used in combination with polyester fabrics. Additional additives and top-coatings are generally used to improve the fire behaviour, the expected lifespan, the self-cleaning properties and the colour stability. PVC is the most used coating for architectural fabrics due to the reduced cost, the easy weld ability (high frequency, hot air) and the range of colours available. In addition, it can be easily painted or printed. In order to obtain a non-stick, self-cleaning surface resistant to UV rays, PVC is generally combined with a top-coating based on acryl, polyurethane (PU), polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF). PVC coatings, combined with adequate topcoats, have a life span of more than 20 years.

In order to reduce the high environmental impacts related to the use of PVC, new alternative coating are currently under development.

2.1.2.2 Fluoropolymer Coatings

Despite the higher price, fluoropolymer is the most common material for coatings when there are requirements for particularly high resistance to UV radiation and to chemical and biological corrosion. The range of fluoropolymer coatings is quite wide and includes PVF, PVDF and ETFE.

Polytetrafluoroethylene (PTFE) is the strongest bond in organic chemistry and the most used fluoropolymer coatings (PVF and PVDF are mainly used as top-coatings for PVC. THV has been only recently used in combination with polyester fabrics due to the extremely high resistance to corrosion. Its colour is always off-white becoming almost white with UV radiation (Bayer 2010).

2.1.2.3 Silicone

Silicone is mainly used in combination with woven glass fabrics due to the high flexibility and light transmission. It is relatively cost effective and has excellent characteristics of UV and flame resistance. It is considered the most environmentally sustainable coating with great potential for the future (Goldsmith 2013).

Its principal drawback is that it tends to pick up airborne particles and dirt. In recent years, new formulations have been developed to address this issue. The main technical limit is represented by the seaming process which requires PTFE threads or silicone adhesive tapes.

2.1.2.4 Polyurethane

Thermoplastic polyurethane is a polymer composed of a chain of organic units joined by urethane links. Compared with PVC it has higher properties in terms of elasticity, transparency, and resistance to oil, grease and abrasion. Due to the relatively high cost and the progressive yellowing, its use is restricted to special applications such as biogas plants and flexible tanks. It is easy to weld and due to the higher airtightness it is commonly used for pneumatic structures such as inflatable tents and boats.

2.1.2.5 Polyethylene

Polyethylene coatings are used for cost effective alternative to more durable coated fabrics when a shorter lifespan is acceptable such as temporary shelters and ground sheets. Polyethylene coatings are available in a quite wide range of colours with a relatively high translucency or with a blackout fabric. They are generally used combined with polyethylene woven slit weaves and can be welded easily.

2.1.2.6 Synthetic Rubbers

The use of coatings based on synthetic rubbers for architectural fabrics is relatively restricted due to the cost. Neoprene is one of the most common rubber coatings for architectural uses thanks to its flexibility over a wide temperature and the resistance to corrosion, degradation and abrasion. It is used for high quality inflatables for heavy duty applications such as boats and tents.

2.1.2.7 Low E Coatings

Due to the increasing demand of coated fabrics with better thermal performance, the so-called low E (low emissivity) coatings are becoming more popular for architectural fabrics. They are mainly based on the same technology used for insulating glass and consist of an ultra-thin metallic coating based on fluorinated tin oxide or thin silver layer(s). The result is a considerable reduction of the heat losses from the interior.

2.1.3 Coated Fabrics

Coated fabrics are the result of the combination of the fabric and the coating. The coating is generally applied on both sides and can be the result of several layers and materials. The yarns can be combined according to different geometries which lead to different properties, depending on the final use. According to the principle used they can be divided into woven fabrics, knitted fabrics and non-woven fabrics.

Woven textiles are the most used type of fabric for architectural uses; the structure is based on two types of yarns: the warp and the fill. The warp yarns are positioned on a loom and the weft yarns are passed over and under in order to make cloth. The weaving process can follow different patterns, leading to different aspects and properties. The most common are the plain weave, the basket weave, the satin weave and the twill weave. During the weaving process the yarns undergo different levels of curvature, depending on the pattern adopted, with a consequent reduction in their tensile resistance.

Knitted fabrics, divided into warp-knit and weft-knit, include several types of fabrics obtained through the interlocking of loops of yarn rather than interlacing two sets of yarn, as in weaving. This geometry leads to a fabric that is more elastic and form-fitting than counterparts made from a woven fabric, a characteristic much appreciated when the fabric is used to reinforce a complex three-dimensional surface. However, the high level of curvature leads to a stress concentration in the yarns, with a consequent reduction in the maximum tensile strength (Rudd et al. 1990).

Non-woven fabrics present a structure obtained by putting small fibres together in the form of a sheet and then binding them either with an adhesive or by interlocking them with serrated needles in such a way that the inter-fibre friction results in a strong fabric. Their production is generally less expensive than woven and knitted fabrics and the overall behaviour is characterised by a low level of stretch and a higher tensile resistance due to the absence of damage caused by the curvature of the yarn (Piggott 1995; Fisher et al. 2003).

There are a wide range of coated fabrics for architectural applications, their use is generally related to their behaviour in terms of mechanical strength, flex cracking resistance, protection against the effects of weather, fire protection, light transmittance and price.

2.1.3.1 PVC-Coated Polyester Fabric

Polyester-PVC is one of the most used textile membranes in the building industry due to the good compromise of price and performance. The five types of polyester woven fabrics cover a wide range of tensile strengths suitable for all the main structural applications. In addition, thanks to a relatively good flex cracking resistance, this type of fabric is also successfully used for deployable structures. The main limitations of PVC-coated polyester fabrics are related to the light transmittance, the resistance to soiling and the long-term stability (which, however, can be considerably increased through top coats made from fluoride lacquer).

Its successful use for tensioned façades is well-documented by a wide range of projects all over the world where cost-effective solutions and short to medium service life are required, such as most of the recent structures designed for the Olympic Games in London. Furthermore, its use for temporary pavilions is widely supported by the possibility of recycling the coated fabric, thereby reducing its environmental impacts.

2.1.3.2 THV-Coated Polyester Fabric

The use of THV coatings as a replacement for PVC is quite recent in the building industry with little data and examples regarding their use. Despite the limited data available, compared with PVC coatings THV is supposed to offer a better behaviour in terms of weathering resistance, self-cleaning properties, light transmittance and UV resistance with the advantage of a similar manufacturing process and equipment.

2.1.3.3 PTFE-Coated Glass-Fibre Fabric

Considered one of the most durable membrane materials, glass-fibre fabric coated with PTFE is the most recommended material for permanent projects with an expected service life over 25 years. The material, characterised by a good light transmittance, combines the advantages of the PTFE coating, which provides excellent long term stability and resistance to soiling, with the mechanical resistance of the glass fibres. However, the relatively high cost of the material, especially compared with Polyester-PVC, combined with the additional manufacturing and installation costs due to its low flex cracking resistance, has reduced its use for temporary and low budget projects and for geometries with a high level of curvature.

PTFE-coated glass-fibre fabrics have been used for several high quality tensioned façades such as the Berlin Brandenburg Airport and the Burj Al Arab Hotel in Dubai.

2.1.3.4 Silicone-Coated Glass-Fibre Fabric

The disadvantage of PTFE-coated fabrics, which are susceptible to wrinkling, is overcome by using clear or opaque silicone treated with additives. Silicone shows an excellent light transmittance, flex cracking performance and resistance against chemical attack and UV radiation, and it does not become brittle. One disadvantage is that its surface charges up statically and attracts dirt. In addition, the high cost of the raw material and the relatively complex and expensive manufacturing process (the material has to be vulcanised or glued) reduces its use in architecture.

Due to the price and the performance, Silicone-coated glass-fibre fabrics are mainly used for permanent applications such as the Zenith Concert Hall in Strasbourg.

2.1.3.5 Coated and Uncoated PTFE Fabric

The main properties of PTFE fabrics are their extremely high flex cracking resistance, light transmission, long-term stability and resistance to soiling, which make it the most recommended material for convertible structures, especially when uncoated and with no budget restraints. Its relatively infrequent use for façades is mainly due to the high price of the raw material. However, the potentialities of PTFE fabrics are clearly expressed by recent project such as the façades of the clusTEX research pavilion in Milan and the NRW Bank travelling exhibition ship.

2.1.3.6 PU Coated Nylon Fabrics

Polyurethane coated nylon fabrics are characterised by and extreme flexibility and light transmittance. Due to the relatively low mechanical performance of the nylon fabrics, is generally used for small projects. The coating is easy to weld and provides a good level of airtightness which makes PU coated fabrics the best solution for pneumatic products. When required, higher mechanical performance can be achieved by using polyester fabrics.

2.1.4 Open Mesh Fabrics

Open mesh fabrics are the result of increasing use of permeable textile for the solar control. They are made by the same fibres and coating used for coated fabrics but they are designed with a specific level of permeability to light, wind and rain.

The behavior of the open mesh fabrics is influenced by the coating process adopted. The coating layer can be applied to the single yarn before the weaving process (lower shear stiffness) or applied through the doctor blade, dip coating and lamination.

Knitted high density polyethylene shade fabrics are probably one of the most promising materials due to the extremely reduced cost, the relatively high life span and the extraordinary elasticity.

2.1.5 Foils

2.1.5.1 ETFE Foil

ETFE is one of the most stable chemical compounds and its films are largely employed in the building industry due to the very good long-term stability, resistance to soiling and high light transmittance. The mechanical strength is relatively good, especially considering that the material is not reinforced by a woven support, and make ETFE foils suitable for load bearing envelopes characterised by small spans or supported by cables. The best known ETFE façade is the Beijing Aquatics Centre, however, the material has been recently used for single layer projects such as the Unilever building in Hamburg.

2.1.5.2 PVC Foil

PVC foils are characterised by an extremely poor mechanical resistance, long-term stability and resistance to soiling. The optical properties, which deteriorate quickly despite the initial transparent and clear aspect, are inferior if compared with ETFE, especially considering specific wavelengths. However, the flexibility of the material and the extremely low cost, make PVC foils a valid alternative for indoor or temporary applications. One of the most relevant projects is the façade for the Finmeccanica Pavilion designed for the Farnborough International Air Show.

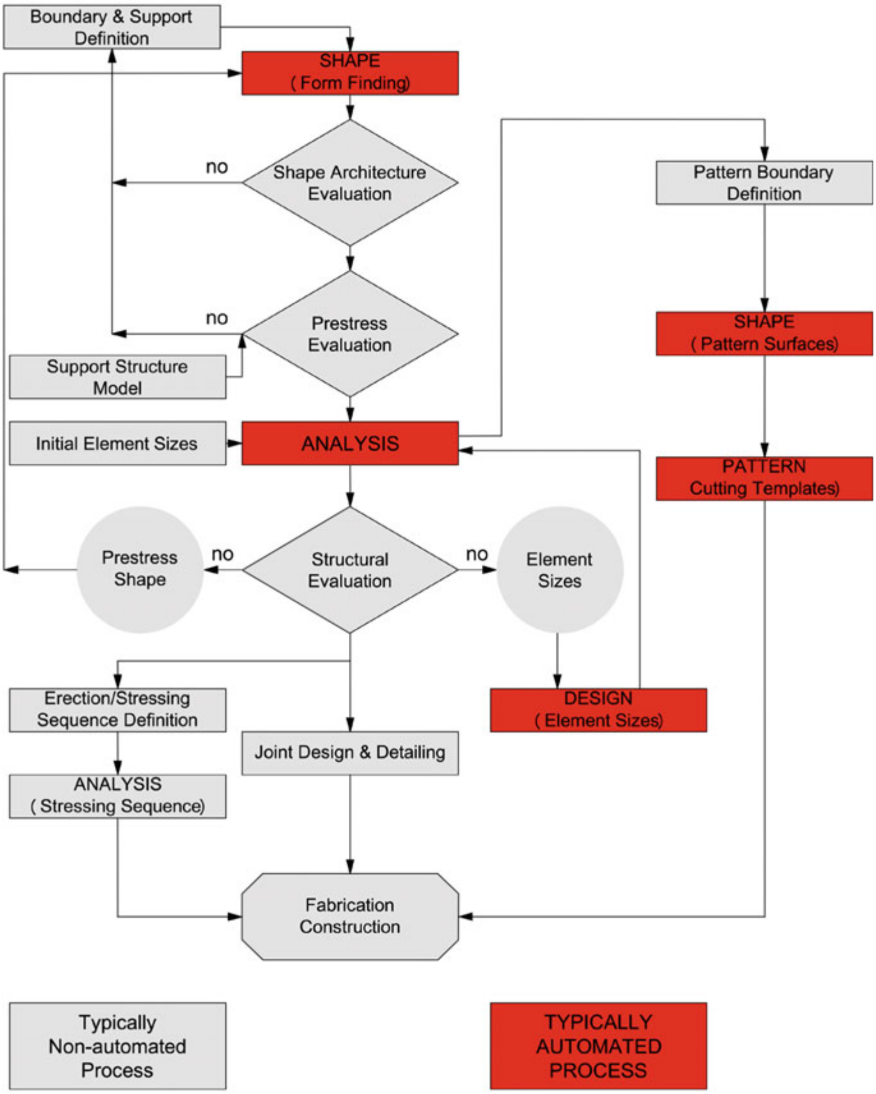

Fig. 2.1 Flowchart illustrating the general approach to tensile membrane structures design and engineering. Modified from Campbell (1991)

2.1.5.3 PE Foil

PE foils do not present any relevant properties for the building sector except for the extremely low price, which compensates for its very poor UV and soiling resistance. For this reason its use is mainly confined to greenhouses and the agricultural field with no relevant permanent projects in architecture. However the film has been successfully used for temporary pavilions and installations such as the Mobile Action Space in Berlin.

2.1.5.4 THV Foil

THV foils offer a good flex cracking resistance and long-term stability comparable with those provided by ETFE foils. However its optical properties and resistance to soiling are considerably lower than ETFE. Although it can be easily welded with high frequency welding machines, its use in architecture is quite sporadic due to the lower mechanical and tearing resistance which reduce its use over medium and large spans.

2.1.5.5 PU Foil

Thermoplastic polyurethane foils are flexible in cold weather, resistant to abrasion and air tightness. Due to the relatively high price, the low elastic modulus (elongation at break up to 800 %) the progressive yellowing and the poor performance at high temperatures clear PVC films are preferable for architectural applications. One of the few exceptions is represented by airtight bladders for inflated structures. Polyurethane comes in two variations: polyester-based and polyether-based. Polyester-based material is subject to early hydrolysis and degradation in many environments that the polyether-based material is not. Heat, oxidation, and certain chemicals will accelerate this degradation. Polyurethane can be recycled easily and does not release hazardous compounds when being processed or recycled.

2.2 The Architecture of Membrane Structures

The unique features of membrane structures are mainly ascribable to the structural behaviour of flexible elements, such as cables and membranes, and their differences compared with the components of more conventional roofs (Chilton 2010).

Elements in pure tension provide the most efficient way to resist external loads. Compared to beams and columns, where part of the material is underutilised or the buckling instability compromises the final residence of the components, cables and membranes can be stressed at the material's ultimate strength. However, due to the similarities with a catenary, the (large) deflection of the structure is directly related with the magnitude and the distribution of the applied loads with several drawbacks in term of structural design. Only an adequate geometry, designed with a correct level of double curvature (anticlastic for pre-stressed surfaces, synclastic for inflated components) can support the downward and upward wind and snow loads without ponding and fluttering problems.

2.2.1 Tension Structures: Definition and Classification

The term tension structures describes the category of buildings in which the load bearing capacity is achieved through tension stress in the majority of the components, such as cables, technical fabrics or foils. The only exception is represented by rigid boundaries and structural members which are generally subjected to compression and bending. Tension structures are commonly subdivided in boundary tensioned membranes, pneumatic structures and pre-stressed cable nets and beams (Lewis 2003).

2.2.1.1 Boundary Tensioned Membranes

These types of structures are realised by means of lightweight (typically 0.7–1.4 kg/m^2), highly flexible membranes with a level of pre-tension which generates stiffness in the surface, the tension state is introduced by means of one dimensional flexible elements such as cables or ties which can be applied as flexible edge boundaries, or in order to increase the surface curvature through ridges and valleys. The overall equilibrium of the structure is provided by rigid edges and supporting members generally subjected to compression and/or bending. The surface load bearing capacity is provided by its double curvature and the pre-tension introduced. The level of pre-stress depends on the material and geometry chosen and it is expressed as a percentage of the strip's ultimate tensile strength (EN ISO 1241:1998), generally 2.5 % Ultimate Tensile Strength (UTS) for PTFE-Glass fibre fabrics and 1.3 % UTS for PVC-polyester fabrics (Bridgens et al. 2004). Under imposed load due to snow or wind, the fabric surface undergoes large displacements and a consequent increase in the material stress, which can increase up to ten fold. It has been noted that at 25 % of the UTS, tear-type damage becomes unstable and starts to propagate, leading to membrane failure (Happold 1987; Blum and Bögner 2007). For this reason a safety factor higher than four is highly recommended. The relatively recent application of this structures does not offer complete statistical data about the reliability of joints and material properties, both in the short and the long term; for this reason continual research is required in order to assess and develop new solutions and details.

Membrane structures are basically realised with coated fabrics, with growing interest towards open mesh coated fabrics and foils. Coated fabrics were originally obtained from natural fabrics such as cotton, but they have been progressively substituted with ceramics (glass fibre) and synthetic organic fibres such as polyester, which offer increased performance regarding strength, water proofing and resistance to chemical attacks. While the mechanical resistance is determined by the yarn dimension, the fibres used and the weaving pattern, the other fabric properties are principally due to the polymer coatings applied to the fabric, improving the shear stiffness, water tightness, fire resistance, self-cleaning properties and UV-resistance. Depending on the fibres used in the fabric, several materials can be used for the coating layer, such as polyvinylchloride (PVC), polytetrafluroethlyene (PTFE), polyvinylidine difluride (PVDF) and silicone, each of them having considerably different characteristics as described in Sect 2.1. ETFE foils are traditionally used for multilayer pneumatic cushions, however, in recent projects, such as the Unilever headquarters in Hamburg Hafecity (Stimpfle 2010), the application of single skin ETFE foils has been successfully investigated. This innovative application opens new areas of interest in the area of the building envelope, such as a protective secondary facade. In addition, the growing demand for reducing the heating\cooling costs has recently increased the demand for open mesh coated fabrics which are able to modulate the amount of radiation reflected, absorbed and transmitted through different weaving patterns and coatings.

2.2.1.2 Pneumatic Structures

The term pneumatic structures includes all the lightweight structures in which the load bearing capacity is achieved by means of air under pressure. They are mainly subdivided into two categories: the buildings characterised by a single layer, stabilised by a slight difference in pressure between the inside and the outside of the structures, and the building envelopes stabilised by air under pressure enclosed between two or more membrane layers.

The basic idea of single layer pneumatic structures is quite simple, an internal volume delimitated by the thin membrane is maintained under pressure by means of fans, a low level of pressure leads to a distributed force on the membrane surface, which receives the support necessary to compensate for the self-weight and the external loads, assuming the classical synclastic curvature. This type of structure is generally designed to maintain an internal pressure between 0.2 and 0.55 kN/m^2, which assures the necessary stability for wind loads but can be inadequate for heavy snow falls. The snow loads, which can reach a value on plan from 0.2 to 2.4 kN/m^2, represent a critical aspect of these structures which can be overcome heating the internal air space. If the stabilising forces do not exceed the external loads, due to overloading or dysfunctions in the internal control system, dimpling occurs in the membrane and the reversion of the surface curvature can lead to the collapse of the structure, with consequent damages to the structure and its occupants. Air-supported structures provide a cost effective alternative for seasonal wide span coverings, nevertheless, the reduced resistance under bad weather conditions combined with high costs due to great pressure losses, reduced insulation, maintenance and the seasonal mounting and dismounting costs can progressively reduce the initial convenience over the entire life span (Shaffer 2013).

Some critical aspects can be reduced by adopting a multiple layer solution. It has been widely demonstrated that envelopes with cushions realised with two or more layers of material show a higher thermal insulation (Devulder et al. 2007; Schmid 2007; Ward et al. 2010) and lower pressure losses despite an increase in the complexity of the pressure control system. Moreover, the load bearing capacity of structural elements can be increased by including cables and steel bars, which can increase the resistance in tensioned and compressed areas. The synergetic combination of pneumatic fabric structures with cables and struts is at the basis of the Tensairity® system, which stabilises lightweight struts under compression through a pressurised cylindrical cushion and two tensioned cables, increasing considerably the load bearing capacity of the pneumatic beam (Pedretti and Luscher 2007).

2.2.1.3 Pre-Stressed Cable Nets, Beams and Domes

Cable structures are load bearing structures composed of linear flexible elements under tension, with the only exception being rigid members or supports such as rigid ring beams or masts. They can be subdivided in cable nets, which describe three-dimensional surfaces, cable domes and their two-dimensional version represented by cable trusses.

Despite the overall complete difference aspect, cable nets share the basic physical principles which regulate their equilibrium and shape with the boundary tensioned membranes described above. According to Lewis (2003), from the point of view of an analyst it can be said that they represent a discrete-type of membrane with no considerable differences, therefore they can both be called a tensioned structure. This argument is reinforced by the historical evolution of this type of structure which, at the early stage when technical fabrics did not provide the necessary resistance, were realised by means of a load bearing cable net structure under pre-tension, with a further layer made by one of the first examples of coated fabric. One common configuration is based on rigid edges made by steel or concrete under compression, on which the cables are anchored and tensioned obtaining double curved anticlastic surfaces in which each node is stabilised by force in opposite directions in equilibrium. If the surface assumes a synclastic configuration the equilibrium is achieved by means of heavy roof cladding, which prevents the surface lifting in the presence of wind. The second alternative is the use of flexible edge cables supported by masts and tie backs.

Cable domes are based on a slightly different structural scheme which is generally circular in plan and based on radial trusses made of cables with the only exception of vertical compression struts.

Cable trusses mostly present a planar structure, with a top cable and a bottom cable with a considerable cross-sectional area due to their load bearing function. They are separated by means of hangers which contribute to the stress distribution of the two main cables. The structural equilibrium is obtained with geometries and a pre-tension which prevents compression stress states in each cable or hanger, in the case of suspended geometries the stability is achieved with heavy suspended loads. Cable trusses often incorporate struts under compression in order to reduce the level of flexibility.

The load bearing capacity of pre-stressed cable nets, domes and beams depends on the geometry chosen, the level of pre-stress and the allowable deformation and fatigue strength of each member, the higher the pre-tension the lower the deflection under external loads, but with a consequent increase in costs and material stress.

2.2.2 Tensioned Membranes and Conventional Roofing Forms

The design of tensioned membrane structures is a relatively new branch of architecture and engineering and is based on different assumptions. Compared with conventional rigid structures, membrane structures define their own contour on the basis of the boundary conditions, the material properties and the level of pre-stress into the surface. In addition, membrane structures accommodate loads through changes in surface tensions and very large displacements, producing a geometrically nonlinear behaviour which requires specific design software. The level of pre-stress is fundamental for an adequate resistance to the applied external loads and is a tradeoff between the risk of ponding and fluttering on one hand, and the risk of tearing on the other. Cables and membranes are generally characterised by an intrinsic nonlinear behaviour mainly due to the geometrical layout of yarns and wires. This results in relatively high costs for the computational analyses which should be added to the intrinsic cost-effectiveness of this type of structures.

These features highlight the fundamentally different approach between conventional roofing forms and tension membranes which require a tight collaboration between the subjects involved in the design and realisation of this type of building. Considering the design phase, it can be seen that ordinary structures are generally the outcome of two different protagonists: the architect, in charge of the initial proposal and its development from the aesthetical point of view up to the singular detail, and the engineer responsible for the static equilibrium of the structure, which has to meet the aesthetic requirements within a reasonable cost and feasibility of the structure. This approach is practicable because the rigid-type constructions are characterised by small deformation, thus there are no considerable consequences on the geometrical shape, which is generally chosen at priori with limited attention to the structural problems investigated by the engineering office once the project is approved. The same organisation characterises the building erection with reduced collaboration between the companies involved, who are generally responsible for the execution of a single activity, with no considerable consequences for the other phases.

This methodology is totally inadequate for tension membranes, the aesthetic issues go hand in hand with the structural aspects because the overall shape of the structure depends on its equilibrium. Thus, the membrane shape cannot be imposed, but it has to be found by working on the boundary conditions and the internal stress distribution due to pre-stress. This imposes a tight cooperation between architects and engineers in the design phase, which should consider the technical limitations due to material production, erection and maintenance. For this reason the manufacturer and material producer are generally involved at the early stage of the project development, which should consider aspects related to the chosen material and the technology available at the workshop in charge of the manufacture of the structure (Fig. 2.2).

The comparison between conventional roofing forms and tensioned membranes is generally based on the mere confrontation of a few parameters which generally comes

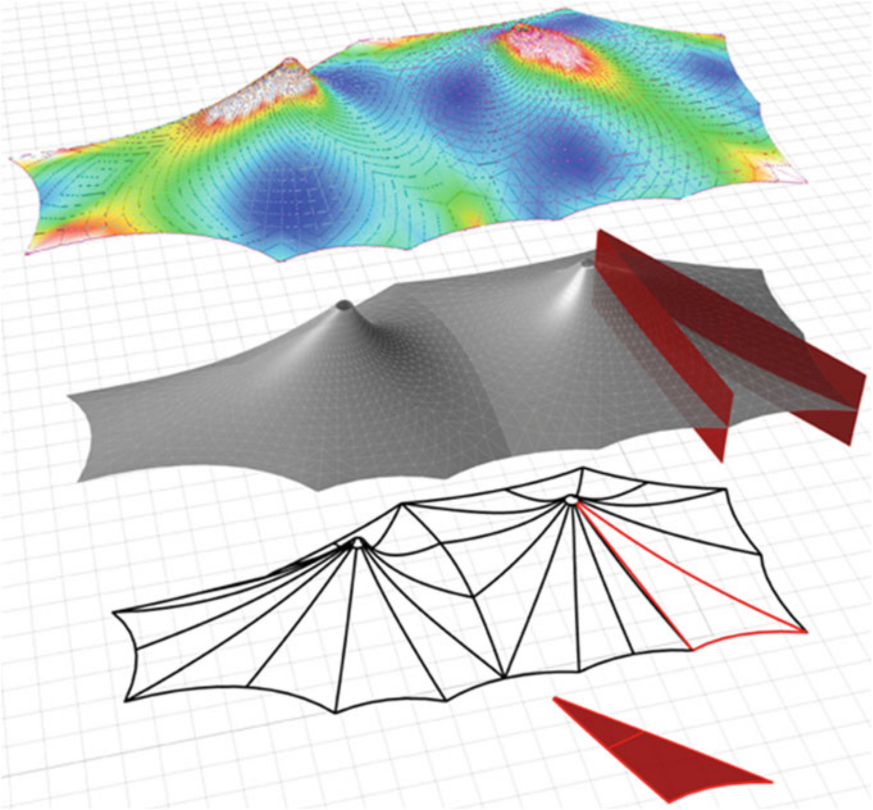

Fig. 2.2 Design process for membrane structures: form-finding, structural analysis and cutting pattern for a double cone tent

from the evolution of the building technology. The expectancies about parameters concerning the mechanical properties, the thermal and acoustical insulation, the durability and so on, depends on a long building tradition based on concrete, steel, timber or masonry and does not describe efficaciously the potentialities of lightweight structures. A superficial comparison can result in the perception of membrane structures as a cheap, temporary version of permanent rigid structures, with a consequent race to increase their performance at any cost, resulting in the loss of the original lightness and translucency. Whereas the strong points of tension structures are their lightweight and the efficiency with which the material is used.

This approach is particularly suited to temporary structures, deployable structures, emergency shelter and wide span structures and offers interesting opportunities concerning the reusability of building components and their recycle at the end of the life span.

2.2.3 The Design Process

The design of traditional rigid structures follows a linear sequence in which the initial architectural shape is transmitted to the engineering office in charge of the structural design; subsequently once the architectural shape has been upgraded in accordance with the structural requirements, the definitive project is transmitted to the builder for the realisation of the construction. The correlation between the several subjects is generally reduced to the correct information transfer between two consecutive phases. Only masterpieces of modern architecture and engineering are an exception to this procedure.

Whereas, the initial shape of membrane structures is the result of a preliminary structural analysis called "form-finding", which assures that each point of the surface is in equilibrium, given the tension ratio in warp and fill direction and the boundary conditions. The architectural and the structural idea should converge to a solution which is both aesthetically pleasing and structurally efficient and feasible. The design process cannot leave out of consideration the issues related to the material chosen, the manufacturing and the erection. It is therefore desirable that manufacturers and material producers are involved in the project development at the earlier phases of the projects, when the type of membrane material is selected, with consequent repercussion on the joints realisation and assembling procedure (Fig. 2.1).

The design process of tension membranes can be summarised in three main steps: the form-finding, the static analysis and the patterning, with the possible addition of dynamic analysis if required (Fig. 2.2). Nowadays, these steps are the key features of several software programmes used in the design of membrane and cable net structures, according to the target considered by the developers, the design software includes one, two or all the modules. However, before the spreading of the computerised design methods, these steps were carried out by means of physical models with accuracy and scales of representation depending on the technical aspects investigated.

2.2.3.1 Form-Finding

Through the form-finding process the initial, equilibrated shape of the structure is determined. As described above, the initial shape of a membrane structure is a function of the stress ratio in a warp and fill direction and the boundary conditions; external loads are not considered at this stage. The membrane configuration in the three-dimensional space cannot be imposed at priori and is the result of an accurate calibration of the various parameters and the combination of the basic shapes, such as cones, ridge and valley, barrel vaults and hypars.

According to Lewis (2003), this term can have three different meanings: firstly, "finding an optimal shape of a tension membrane" which is fundamental in studies on stable minimal surfaces, secondly "finding a shape of a tension membrane that is in static equilibrium, but does not necessarily have constant surface stress" and thirdly, “finding a shape which approximates the state of full static equilibrium”, which is of particular interest in some design approaches which combine patterning with form-finding.

In absence of the current computerised software, this phase was initially carried out by means of physical models. Several important realisations, such as the Olympic Stadium in Munich, have been designed through this approach, combined with a very simple computerised method (Songel 2010).

Although physical models represent a valid method for visualization purposes, it has to be said that they lead to inevitable problems due to the correct determination of the local stress state, the deflection under load and the error magnification when the measures carried out on the model have to be scaled up to the full-size. Soap films represent an extremely interesting type of physical model because of their capacity to span an arbitrary boundary condition with a stable minimal surface, characterised by a uniform stress state in a warp and fill direction. This type of surface shows interesting physical and mathematical properties and has been adopted in several structures because of the minimal quantity of material required and the homogeneous stress distribution which optimises the use of the material. However, this approach reduces to one the possible shapes obtainable from a given boundary, varying the stress state and, in addition, it is not universally accepted because it is argued that the optimisation is valid only for one load condition, the initial pre-tension, without considering the infinite load combinations which the structure will undergo during its life span.

The intrinsic limitations of physical models, their considerable cost and the time required to achieve them, and adequate accuracy for each refinement and change of the surface, lead to the progressive interest towards computerised methods. The force density method (Schek 1974) is analytic technique to linearize the form finding equations which has been successfully used in several computer software packages for the determination of the equilibrium shape due to a specific prestress in warp and fill direction. The method provides the equilibrium geometry of the membrane on the basis of a certain topology and a set of force density ratios, given by the cable force divided by the cable length. By choosing an equal and uniformly distributed force density for all elements, it is possible to generate the same minimal surface obtained through soap film models. Comparable results can be obtained by using the dynamic relaxation method (Barnes 1984) which addresses the geometrically non-linear problem by equating it to a dynamic problem which can be solved through well-known techniques for dynamic problems (Ishler 2013).

2.2.3.2 Static Analysis

The static analysis is performed assuming as initial configuration the one determined in the form-finding stage. Through the static analysis it is possible to predict the stress and the displacements which arise in the tensioned surface due to the presence of external loads such as snow or wind. According to the current European design code or the national set of rules, it is necessary to consider the most significant loading conditions obtained by the combination of the expected loads with safety factors, due to the uncertainty concerning their assumed magnitude and position. The analysis results are generally represented by means of coloured patterns distributed on the structure, which indicate, for each loading condition, the value of the parameter considered (stress, strain, deflection, etc.). Moreover, for further detailed consideration, the values are generally available in the form of a database divided for each element.

Despite the similarities with static analysis currently carried out for traditional structures, the assumptions of small deflections and the linear behaviour of both material and structure, are not suitable for tensioned structures. For this reason the mathematical models employed are completely different compared with those commonly used, and should follow an iterative computation able to determine the final equilibrium form.

The determination of stress distribution is a crucial step in the design process, since the membrane choice or the detail resistance depends on the maximum value noticed.

2.2.3.3 Dynamic Analysis

The scope of dynamic analyses is the evaluation of the interaction between a fluctuating external load and the structure. For membrane structures this issue is generally related with the fluctuation of wind pressure. In the presence of certain conditions, a negligible deflection can lead to the collapse of the structure. The accuracy and reliability of the simulating software has increased considerably in the last decade, allowing their wide use for preliminary investigation and standard realisations (Hart et al. 2010). However, for projects with particular relevance or for the validation of simplified models for standard applications, the expected data should be confirmed through tests performed in a wind tunnel.

The wind tunnel tests are highly specialised experiments which require expensive instrumentation originally developed for aeronautic purposes. Their use for civil applications, such as suspended bridges, requires larger chambers with consequent increases in costs, and there are few research centres available. Through the use of rigid models equipped with sensors of pressure, the wind force distribution on the rigid surface can be individuated, which reproduces, in scale, real environmental conditions. This approach aims to obtain the wind force distribution under significant boundary conditions which are the necessary input for simulating software. It does not consider the deflection of the surface under wind pressure and the next effects on their distribution. More accurate investigations aim to reproduce the dynamic interaction between wind pressure and the flexible surface which reproduce, in scale, the in situ elastic material properties.

2.2.3.4 Patterning

Through the patterning design stage, the three dimensional surface, found by means of the form-finding, is flattened, obtaining a two dimensional cutting pattern for the manufacturing of the fabric canopy, beginning from rolls of materials from 1.80 to 3.00 m wide. This operation is generally based on mathematical studies carried out for several applications, such as the determination of the surface area of solids or the topographic issues related to the realisation of accurate bidimensional maps of the globe. It has been demonstrated that this operation cannot avoid a certain amount of error during the transformation of a three-dimensional shape into a two-dimensional surface. Physical models were widely used for this operation but the increasing accuracy of computerised software has progressively reduced their massive use to a simple interactive comparison of the results obtained through software. Moreover, the level of accuracy can be influenced by the application of a procedure which aims to obtain smooth cutting lines despite a slight increase in error.

2.2.4 The Manufacturing Process

Once the design phase is completed, the working drawings are transmitted to the companies in charge of the realisation of the structure which can be subdivided in the foundation, the supporting frame and the membrane. Through the manufacturing process, the flat membrane produced in rolls is converted in a double curved continuous surface (Chilton 2010).

The use of a membrane envelope intensifies the level of industrialization of the construction, reducing the number of processing phases and workers involved in the on-site construction, and increases the proportion of factory-built components which are only assembled on-site. This has several advantages in terms of efficiency (1–10 m^2 of material processed for each hour of work, according to the material and the type of joints chosen) and quality of the final product.

The working drawings are the result of the flattening of the three-dimensional shape obtained through the patterning process, the initial shape should be adequately compensated and provided with the extra material necessary for the welding process and joint realisation. The layout used for the cutting pattern is generally chosen in order to emphasise the aesthetic result and to minimise the material waste and the number and length of the seams (manufacturing costs). The shape of the patterned panels is related to the cutting lines, with the curved boundaries of the long thin strips relatively straight when generated by geodesic lines. One of the most common techniques for the development of the patterns is based on the subdivision of each "strip" of the surface in triangles which are then laid down on a plane (Daugherty 2013).

Once the fabricator receives the necessary material from the material producer, which for orders that exceed one thousand meters can personalise the colour and other treatments, the material correspondence to the required specifications are controlled through tests such as the uniaxial strip tensile tests. Then, the roll of material is controlled through a light table in order to individuate the presence of local defects (which should be already marked by quality control of the material producer) and positioned on the manual or automated cutting table. The strips of fabric are cut out of the roll, with a maximum width generally between 1.80 m and 3.00 m, avoiding local damages. They are then joined together in order to obtain the biggest panel of fabric transportable and mountable, reducing the use of welding machines or other high precision processes on the building site. The seams between the panels of fabric are generally based on heat or high-frequency welding which provide a higher level of water-and airtightness. However, glued or mechanical stitching, clamping or lacing are also possible according to the specific requirements.

Thanks to the relatively low transportation costs, the packed structure can be delivered all over the World using trucks, railways, waterways or even aeroplanes when required, virtually with no limits in terms of logistics. However, this operation is critical for the membrane, which could easily be damaged by an incorrect folding process or by the presence of rigid elements which can lacerate the fabric or compromise the protective layers. Depending on the material, special attention should be paid to the maximum allowable folding radius. This is particularly important for PTFE/Glass fibre fabrics which generally require the use of soft cushions which reduce the folding radius and the risk of damage to the yarns with the consequent lacerations. For complex realisations, the folding and unfolding procedures should be carefully considered in order to follow and facilitate the mounting plan and reduce unnecessary movements on site.

Once on site, the assembly process is relatively fast and efficient due to the high level of accuracy of manufacture, the adjustable boundary details and the reduced weights and volumes to be handled, which require less (and smaller) lifting equipment. In addition, there are no limitations in terms of combination with others building materials such as steel, aluminium, wood, reinforced concrete, composites etc.

2.3 Testing Standards and Designing Codes

At present, the international normative concerning the design and realisation of tensioned structures is characterised by considerable deficiencies especially on the aspects concerning the membrane surface (or the cable net). Despite the structural behaviour of tensile membrane structures is based on well-established principles of mechanics these structures are

> […] often outside the realm typically considered for building structures (Ishler 2013, p. 94).

In addition,

> […] there is no Load Resistance Factor Design standard methodology for tensile membrane structure [and] as a consequence of their non-linear behaviour LRFD methodology can result in significant difference in design outcome from Allowable Stress Design (Campbell 2013, p. 52).

The main discrepancies with the current building codes are mainly related with the design loads and the safety factors. The structural analyses are based on the most unfavourable load combinations, however, the direct use of the load distributions prescribed by the designing codes, developed for standard buildings, leads to several inaccuracies due to the non-linear behaviour of membrane structures and their large deflection behaviour. Super position of load effects is not applicable to membrane structures and a different load distribution can easily result in an unexpected deflection which can lead to water ponding and snow drift with the progressive collapse of the structure. On the other hand, seismic loads, which are particularly insidious for standard building, are generally negligible due to the low mass of tensioned membrane structural systems. Even the concept of tributary area for live loads is not literally applicable to membrane roofs. In addition, the unique surface forms prevent the direct use of the coefficients for the snow distribution and the wind pressure provided by the designing codes for standard geometries.

In the European context, the common approach for the design of buildings and other civil engineering works and construction products is provided by a series of ten European Standards (EN 1990–EN 1999) known as EN Eurocodes. Their area of applicability is extremely wide from the basis of structural design to the actions on structures, in addition they describe the design procedures and the theoretical aspects concerning each main building system (concrete, steel, composite steel and concrete structures, timber, masonry, geotechnical design, design of structures for earthquake resistance, aluminium). The design of the rigid frame supporting the tensile structure is generally carried out according to the prescriptions reported in each Eurocode (steel, timber and aluminium), however, the most demanding part of the project, the membrane or the cable net, is at the discretion of the designer.

The only European Standard currently available about membrane structures is the EN 13782:2005 "Temporary structures-Tents-Safety". Its area of applicability is mainly restricted to the safety requirements for tents which need to be observed at design, calculation, manufacture, installation, maintenance, operation, examination and testing of mobile, temporary installed tents of more than 50 m^2 ground area. Nonetheless, it offers the only reference to membrane structures and deals with the fundamental terms and definitions, the general requirements for design, analysis and examination, principles of numerical analysis, the design actions, the verification of stability and equilibrium, the ground anchorages, the other structural components, the special design and manufacture criteria, the manufacture and supply, the examination, the competence, procedures for approval, examination and tests, the tent book, the use and operation, the burning behaviour and the aerodynamic coefficients for round shape tents.

The characteristics, the requirements and the test methods for coated fabrics intended for temporary structure and tents are summarised in the European Standard EN 15619:2008+A1:2010 "Rubber or plastic coated fabrics—Safety of temporary structures (tents)—Specification for coated fabrics intended for tents and related structures". It introduces the idea of different level of performance for each characteristic which allows the choice of the appropriate level of each characteristic (mass per unit area, tensile mechanical behaviour, tear strength, coating adhesion, dimensional stability, colour fastness to weathering and light, susceptibility to the development of microorganisms, appearance, elongation under load after heat exposure, residual deformation after heat exposure and load, water penetration) or reaction to fire in order to obtain a "product profile" which satisfy the requirements of a specific type of use. A similar approach is proposed by the Japanese Standard "Test methods for membrane materials (coated fabrics)—Qualities and performances" developed by the Membrane Structures Association of Japan (MSAJ/M-03:2003).

However, due to the field of application, the contents do not offer an exhaustive description of the design approach and the theoretical aspects concerning the design and realisation of a permanent structure.

For this reason the European Network for Membrane Structures TensiNet developed the TensiNet Design Guide (Foster and Mollaert 2004) which represent the most complete and updated state of the art in this field realised by means of the contribute of several groups of research, designers, material producers, software developers and fabricators operating in Europe.[1] The guide is divided in ten sections (engineered fabric architecture, form, internal environment, detailing and connections, structural design basis and safety criteria, design loading conditions, form-finding, load analysis and patterning, material properties and testing, fabrication, installation and maintenance) and contains detailed appendix concerning Cp Values, testing methods and standards.

The set of guidelines represents the starting point for the development of an assignment for the European Committee for Standardization (CEN TC250 Working Group 5), of the future Eurocode 10. In addition, the development of the new Eurocode is currently supported by one of the working groups of an EU funded research project about novel structural skins.[2]

The future Eurocode will deal with particular criteria for design and calculation (small/large span, temporary/permanent, internal/external, transportable/transformable), methods of analysis, appropriate load assumptions on doubly curved surfaces, material properties and their determination and certification, improved material models, partial safety factors, cutting patterns, analysis of reinforcements, connections and detailing, integrated models, manufacturing, maintenance, examination and testing.

In the United States, the activity of the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI) contributed to the development of several standards and manuals of practice. The most relevant is the ASCE Standard 55-10 "Tensile Membrane Structures". The standard offers an overview of the membrane materials, the connections, the design approach and the prescriptions for an appropriate fabrication and erection of the structure. The section concerning the design of tensile membrane structures provides a set of Load Combinations and

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[1] TensiNet. A Thematic Network for Upgrading the built Environment in Europe through Tensile Structures. EU FP5, project n. G1RT-CT-2000-05010, March 2000–August 2004.

[2] Novel structural skins: Improving sustainability and efficiency through new structural textile materials and designs. EU COST Programme, project n. TU1303: oc-2012-2-13283. November 2013–October 2017. WG5-From material to structure and limit states: codes and standardization.

Strength Reduction Factors in accordance with the design loads prescribed by the standard ASCE Standard 7-98 “Minimum design loads for buildings and other structures”. In addition, it suggests some additional recommendations about the use of wind tunnel analysis in order to investigate the wind pressures (where the shape of the membrane does not fall within the limits of the prescriptive load requirements), the flutter at free edges and the resonance of the entire structures. Additional information are provided by the ASCE Standard 17-96 “Air Supported Structures” and ASCE Standard 19-96 “Structural applications of Steel Cables for Buildings”. The prescriptions of the ASCE Standards are now supported by several manuals of practice which examine in depth several aspects related to the design of tensioned fabric roofs (Huntington 2004, 2013).

References

ASCE/SEI 55-10 Tensile membrane structures. American Society of Civil Engineers, Reston

ASCE/SEI 7-98 Minimum design loads for buildings and other structures. American Society of Civil Engineers, Reston

ASCE/SEI 17-96 Air supported structures. American Society of Civil Engineers, Reston

ASCE/SEI 19-96 Structural applications of steel cables for buildings. American Society of Civil Engineers, Reston

Barnes MR, Wakefield D (1984) Dynamic relaxation applied to interactive form finding and analysis of air-supported structures. In: Proceeding of conference on the design of air-supported structures. The Institution of Structural Engineers, Bristol, pp 147–161

Bayer B (2010) Technical characteristics and requirements of textiles used for building and construction. In: Pohl G (ed) Textile, polymers and composites for buildings. Woodhead Publishing Limited, Cambridge, pp 49–68

Blum R, Bogner-Balz H (2007) Tears and Damages in textile architecture: should tear propagation be considered for design? In: Bogner-Balz H, Zanelli A (eds) Tensinet symposium 2007. Ephemeral architecture, time and textiles, Milano. Clup, Milano, pp 239–248

Bridgens BN, Gosling PD, Birchall MJS (2004) Membrane material behaviour: concepts, practice and developments. Struct Eng 82(14):28–33

Campbell DM (1991) The unique role of computing in the design and construction of tensile membrane structures. In: Proceedings of ASCE second civil engineering automation conference, New York

Campbell DM (2013) Loads. In: Huntington CG (ed) Tensile fabric structures. Design, Analysis, and Construction, American Society of Civil Engineers, Reston, pp 51–55

Chilton J (2010) Tensile structures-textiles for architecture and design. In: Pohl G (ed) Textile, polymers and composites for buildings. Woodhead Publishing Limited, Cambridge, pp 229–257

Corazza C (2006) Mechanical characterization of technical textiles for the screen-printing: experimental tests and numerical analysis. PhD thesis, Politecnico di Milano, Milan

Daugherty HB (2013) Fabrication and construction. In: Huntington CG (ed) Tensile fabric structures. Design, Analysis, and Construction, American Society of Civil Engineers, Reston, pp 138–150

Devulder T, Chilton J, Wilson R, Blum R (2007) Advanced textile skins: predicting the thermal response of complex membrane construction. In: Bogner-Balz H, Zanelli A (eds) Tensinet Symposium 2007. Ephemeral architecture, time and textiles, Milano. Clup, Milano, pp 61–74

EN 13782 2005 Temporary structures—tents—safety. European Committee for Standardisation

EN ISO 1421:2000 Rubber- or plastics-coated fabrics—determination of tensile strength and elongation at break. European Committee for standardisation. International Organization for Standardization

Fisher FT, Bradshaw RD, Brinson LC (2003) Fiber waviness in nanotube-reinforced polymer composites—I: modulus predictions using effective nanotube properties. Compos Sci Technol 63(11):1689–1703

Foster B, Mollaert M (eds) (2004) European design guide for tensile surface structures. TensiNet, Brussels

Goldsmith N (2013) The material characteristics of fabrics. In: Huntington CG (ed) Tensile fabric structures. Design, analysis, and construction, American Society of Civil Engineers, Reston, pp 32–50

Happold E (1987) Design and construction of the diplomatic club, Riyadh. Struct Eng 65(10): 377–382

Hart R, Birchall MJS, Fisher A, Williams C (2010) Smart particles: dynamic wind-structure interaction analysis for tensile structures. In: Bogner-Balz H, Mollaert M (eds) Tensinet Symposium 2010. Tensile architecture: connecting past and future, Sofia. GPS 1900, Bulgaria, pp 69–77

Huntington CG (2004) The tensioned fabric roof. American Society of Civil Engineers, Reston

Huntington CG (ed) (2013) Tensile fabric structures. Design, Analysis, and Construction, American Society of Civil Engineers, Reston

Ishler MW (2013a) Form determination. In: Huntington CG (ed) Tensile fabric structures. Design, Analysis, and Construction, American Society of Civil Engineers, Reston, pp 56–93

Ishler MW (2013b) Load analysis. In: Huntington CG (ed) Tensile fabric structures. Design, Analysis, and Construction, American Society of Civil Engineers, Reston, pp 94–103

Lewis WJ (2003) Tension structures: form and behavior. Thomas Telford, London

MSAJ/M-03:2003 Test methods for membrane materials (coated fabrics)—qualities and performances. Membrane Structures Association of Japan

Pedretti M, Luscher R (2007) Tensairity-patent—eine pneumatische tenso-struktur. Stahlbau 76(5):314–319

Piggott MR (1995) The effect of fibre waviness on the mechanical properties of unidirectional fibre composites: a review. Compos Sci Technol 53(2):201–205

Rudd CD, Owen MJ, Middleton V (1990) Mechanical properties of weft knit glass fibre/polyester laminates. Compos Sci Technol 39(3):261–277

Schek HJ (1974) The force density method for form finding and computation of general networks. Comput Methods Appl Mech Eng 3(1):115–134

Schmid G (2007) ETFE cushions and their thermal and climatic behaviour. In: Bogner-Balz H, Zanelli A (eds) Tensinet Symposium 2007. Ephemeral architecture, time and textiles, Milano. Clup, Milano, pp 115–125

Shaffer RE (2013) History and development of fabric structures. In: Huntington CG (ed) Tensile fabric structures. Design, analysis, and construction, American Society of Civil Engineers, Reston, pp 1–24

Songel JM (2010) A conversation with Frei Otto. Princeton Architectural Press, New York

Stegmaier T, Schneider P, Vohrer A, Planck H, Blum R, Bögner-Balz H (2010) Developing and testing textiles and coatings for tensioned membrane structures. In: Pohl G (ed) Textile, polymers and composites for buildings. Woodhead Publishing Limited, Cambridge, pp 129–188

Stimpfle B (2010) Unilever facade Hamburg, Germany, Job Report. In: Bogner-Balz H, Mollaert M (eds) Tensinet Symposium 2010. Tensile architecture: connecting past and future, Sofia. GPS 1900, Bulgaria, pp 109–116

Ward J, Chilton J, Heslop A, Rowell L (2010) Internal environment in ETFE foil covered building enclosures. In: Bogner-Balz H, Mollaert M (eds) Tensinet Symposium 2010. Tensile architecture: connecting past and future, Sofia. GPS 1900, Bulgaria, pp 129–138

http://www.springer.com/978-3-319-02227-7

Biaxial Testing for Fabrics and Foils
Optimizing Devices and Procedures
Beccarelli, P.
2015, IX, 138 p. 59 illus., 4 illus. in color., Softcover
ISBN: 978-3-319-02227-7