Chapter 2
Ultralight Membrane Structures Toward a Sustainable Environment

Alessandro Comitti, Harikrishnan Vijayakumaran,
Mohammad Hosein Nejabatmeimandi, Luis Seixas, Adrian Cabello,
Diego Misseroni, Massimo Penasa, Christoph Paech, Miguel Bessa,
Adam C. Bown, Francesco Dal Corso, and Federico Bosi

2.1 Introduction

The climate change experienced by our planet has alarmingly escalated in recent decades due to anthropogenic contributors to environmental degradation. The present scale of this global emergency demands urgent and immediate remedial measures to ensure that a safe biosphere prevails for future generations of humanity and

---

A. Comitti · L. Seixas
Department of Mechanical Engineering, University College London, London, UK

CAEMate s.r.l., Bolzano, Italy
e-mail: a.comitti@ucl.ac.uk; luis.seixas.20@ucl.ac.uk

H. Vijayakumaran
Department of Material Science and Engineering, Delft University of Technology,
Delft, Netherlands

Tensys Ltd., Bath, UK
e-mail: h.vijayakumaran@tudelft.nl

M. H. Nejabatmeimandi
Tensys Ltd., Bath, UK

Department of Civil, Environmental and Mechanical Engineering, University of Trento,
Trento, Italy
e-mail: mh.nejabatmeimandi@unitn.it

A. Cabello · A. C. Bown
Tensys Ltd., Bath, UK
e-mail: adrian.cabello@tensys.com; adam.bown@tensys.com

D. Misseroni · F. Dal Corso (✉)
Department of Civil, Environmental and Mechanical Engineering, University of Trento,
Trento, Italy
e-mail: diego.misseroni@unitn.it; francesco.dalcorso@unitn.it

M. Penasa
CAEMate s.r.l., Bolzano, Italy
e-mail: massimo@caemate.com

A. Bahrami (ed.), *Sustainable Structures and Buildings*,
https://doi.org/10.1007/978-3-031-46688-5_2

nature. As a result, the United Nations (UN) has identified climate change as a central challenge faced by the planet, as it intrinsically affects all the *Sustainable Development Goals* (SDGs) set forth by the UN. Among the 17 SGDs stated by the UN, building construction practices have an impactful role in achieving SDG 11 – *sustainable cities and communities*, and SDG 12 – *responsible consumption and production* [1], which highlights the need for a paradigm shift in the construction industry to achieve the clean energy transition.

Building constructions and operations show the highest environmental footprint, with 36% of global energy consumption and 39% of carbon dioxide (CO_2) emissions, the latter greater than transportation (33%) and industrial activities (29%) [2]. A recent report by the United Nations Environment Programme [3] demonstrates that the carbon footprint of constructions is increasing, with 28% of buildings-related CO_2 emissions finding their roots in the use of materials and that the demand for buildings and floor area is growing and expected to double by 2060. Consequently, the requirement for materials will remarkably increase in urban contexts, primarily in Asia and Africa. Under these circumstances, innovative building technologies employing low-carbon materials are of paramount importance in embodied carbon reduction to lower construction-related CO_2 emissions through (i) resource-efficient lightweight building designs, (ii) waste reduction via reuse and recycling, (iii) lifetime extension, and (iv) minimal transportation. Hence, the main challenge in the building sector is seeking and implementing novel construction technologies.

A feasible solution toward the achievement of a sustainable built environment is offered by *membrane*, or *tensile*, structures. This construction type aims to bear the external loads through structural elements acting under tension, differently from the load-bearing mechanisms displayed by traditional structures, namely compressive states for arches, bending-dominated states for frames, and compressive/tensile states for trusses. Consequently, the heavyweight and stiff constructions realized in the past through a considerable amount of concrete, steel, stone, and timber materials could, in some cases, be replaced by lightweight and flexible tensioned membranes. Throughout the centuries, the ratio between the self-weight of a permanent structure and the load it carries, defined as γ, has been decreasing, reaching approximately unity with the advent of structural steel, and falling below 1.0 in the case of tension structures, as depicted in Fig. 2.1. A lower ratio implies a decrease in structural weight and more effective use of building materials. Hence, leveraging on an efficient load-bearing mechanism, membrane structures require a reduced amount

---

C. Paech
sbp – schlaich bergermann partner, Stuttgart, Germany
e-mail: c.paech@sbp.de

M. Bessa
School of Engineering, Brown University, Providence, RI, USA
e-mail: miguel_bessa@brown.edu

F. Bosi (✉)
Department of Mechanical Engineering, University College London, London, UK
e-mail: f.bosi@ucl.ac.uk

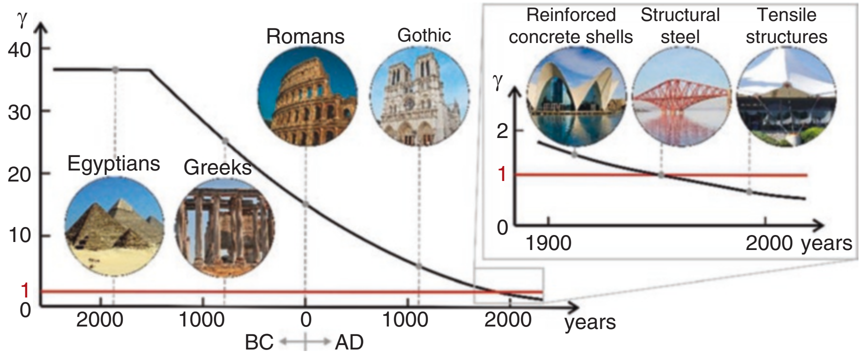

Fig. 2.1 Evolution throughout centuries of ratio γ between weight of a structure and carried load, indicating efficiency of membrane structures [4, 5]

of materials, which in turn reduces the energy and emissions related to their production and transportation.

The efficiency of tensile structures was already exploited by many ancient civilizations around the world. The first examples are the masts of Egyptian sailboats, the movable roofs of Roman amphitheaters, and the tents of Bedouins and Navajo tribes. The possibility to build large-scale tensile/membrane structures has been reached only in the modern era as a consequence of scientific and technological advances. The first large-scale tensile buildings were developed in the second half of the twentieth century, especially for exposition structures. Among the many realizations, the Olympiastadion (Munich Olympic Stadium) by the architect Frei Otto is the most iconic tensile structure of that era [6]. However, at that time, these solutions were limited to temporary installations because of the undeveloped technologies in the material field. Therefore, tensile structures were not yet attractive in terms of durability and sustainability. Nowadays, the technology advances in lightweight materials allow for designing tensile structures with a 30-year lifespan, thanks to improved coatings or foils with superior environmental weathering resistance [7].

As a result of this improved durability, membrane structures are currently employed in a broad spectrum of building applications, such as claddings, roofing, and facades for fairs, exhibitions, and stadia, realizing beautiful envelope designs while pursuing the optimization of resources, Fig. 2.2.

This chapter aims to provide the basics of lightweight membrane structures and the evidence of their role toward green and sustainable constructions. The mechanical principles defining the efficiency of the tensile load-bearing mechanisms in relation to weight and material savings are presented in Sect. 2.2. The technological aspects inherent to the realization of lightweight membranes and the importance of accurate mechanical modeling for optimal material use and safe design are discussed in Sect. 2.3. A quantitative assessment of sustainability aspects is addressed in Sect. 2.4. Each of these sections contains a description of current challenges and

Fig. 2.2 Two examples of tensile structures in large-scale constructions. Left: Glass/PTFE membrane panels for external shading at Hazza Bin Zayed Stadium (© Christoph Paech/schlaich bergermann partner). Right: Membrane roof of Olympic Aquatic Centre, Munich (© Michael Zimmernann/schlaich bergermann partner)

opportunities in the relevant engineering aspect. Lastly, conclusions on lightweight membrane structures are drawn in Sect. 2.5.

2.2 Engineering Design of Ultralightweight Membrane Structures

Membrane structures are an ensemble of lightweight structural elements that combine the principles of aesthetic architecture, material optimization, and structural efficiency. They are advantageous in scenarios where the design has to accommodate large unsupported spans with minimal weight. By building better with less material, environmental benefits in the form of reduced energy usage and carbon emissions during production, transportation, and installation could be accrued, while simultaneously providing a cost-effective structural engineering solution.

2.2.1 Structural and Material Efficiency Through Tensile State

Membrane structures, analogous to their parent class of tensile structures, are designed with the principle of maximum structural efficiency at their core. Bending and torsion are disadvantageous load-bearing mechanisms as the material near the neutral plane is mostly unused. On the contrary, tensile forces generate a constant stress distribution normal to the cross-section, efficiently using all material throughout the thickness and resulting in a significant weight reduction [8]. By remaining in the state of pure tension, membrane structures not only achieve low weight-to-load ratios but also encounter a reduction in instabilities and stress localizations typical of compression [9, 10] and bending-dominated structures [11, 12].

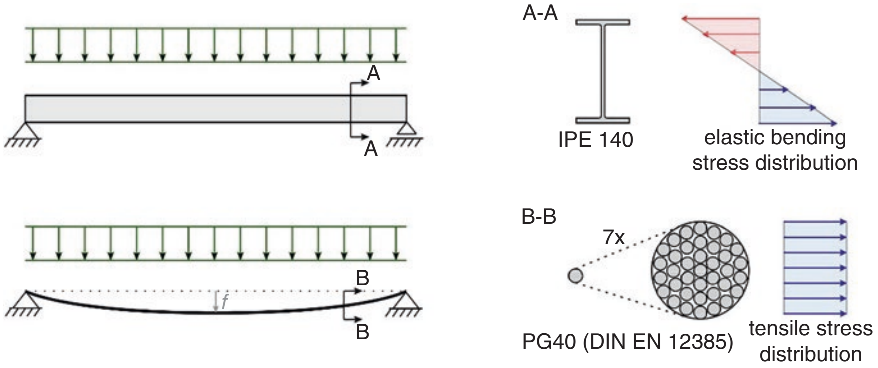

Fig. 2.3 Comparison between bending (top) and tension (bottom) load-bearing elastic mechanisms for a pin-supported structure subjected to the same uniformly distributed load

Table 2.1 Engineering satisfiability and weight comparison of pinned I-beam and cable solutions, associated with bending and tensile load-bearing mechanisms, respectively

Description	I-beam	Cable
Span	4.0 m	
Uniform vertical load	10.0 kN/m	
Ultimate limit state utilization factor	0.65	
Material	Hot rolled steel	Galfan coated steel
Design element	I-section IPE 140 mm (S355)	Spiral strand 1×37, Ø 20.1 mm (PG40 [13])
Weight per meter	12.9 kg/m	1.9 kg/m

To elucidate the efficiency of tension over bending, consider an $l = 4.0$ m pin-supported span subjected to a uniformly distributed load q = 10.0 kN/m, as illustrated in Fig. 2.3. An efficient ultimate limit state (ULS) design in bending can be obtained by using a steel (S355) I-beam of 140 mm height (elastic section modulus S = 77.32 cm^3, sectional area A = 16.4 cm^2), which results in a weight-per-length ratio of 12.9 kg/m. In contrast, the same load can be borne under pure tension by a 20.1 mm diameter steel cable of open spiral strand cross-section (Galfan-PG40 [13], limit design force $F_{u,d} = 222$ kN), assuming the same utilization factor α at the ultimate state and a maximum deflection f equal to the height of the I-beam, such that the tensile force in the cable is $T \simeq ql^2/(8f) = \alpha F_{u,d}$. Such tensile solution has a weight-per-length ratio of 1.9 kg/m, resulting in 85% weight savings. The comparison is detailed in Table 2.1, which demonstrates through the weight-per-length ratio, how a tensile solution with a flexible cable better utilizes the material compared to the rigid I beam. Figure 2.3 compares the cross-sectional stress distribution in the two solutions.

It should be noted that additional mass savings can be achieved if the maximum deflection f is increased, thus decreasing the maximum tensile force in the cable. For example, $f = 200$ mm and $f = 400$ mm would provide 93% and 97.5% weight savings (using Galfan's PG20 and PG5), respectively.

Membrane structures can be considered continuous cable net structures, thus representing the two-dimensional extension of the above-mentioned one-dimensional cable. They are designed to exploit engineering knowledge about the relationship between the nature of load distribution and the deformation states, enabling a plethora of architectural shapes and structural approaches. The components of a membrane structure are assembled such that the loads are primarily borne by the tensile load-bearing elements: (i) the prestressed two-dimensional membrane made of composite/woven fabric or polymeric foils, and (ii) the pre-tensioned one-dimensional cables and ties which form ridges, valleys, and edge boundaries to the membranes. The external loads acting on the membrane element manifest as membrane stresses, as displayed in Fig. 2.4, while those acting on the cable and tie elements take the form of axial forces. These tensile load-bearing elements then transfer the loads to the structural support framework composed of trusses, masts, and beams, which are designed to withstand compression, bending, shear or torsion loads.

The efficient load transfer mechanism of membrane structure relies on prestressing the tensile load-bearing elements, which are inherently flexible. If these elements are not pre-tensioned during installation, they would go slack and undergo considerable displacements, becoming highly susceptible to structural instabilities such as flutter and wrinkling [14, 15]. Based on the method of pre-tensioning of the membrane elements, we can distinguish them as *boundary-tensioned* and *pneumatic* membrane structures. The load-bearing mechanisms of the two categories are different, as are the engineering principles guiding their design. A resource-efficient

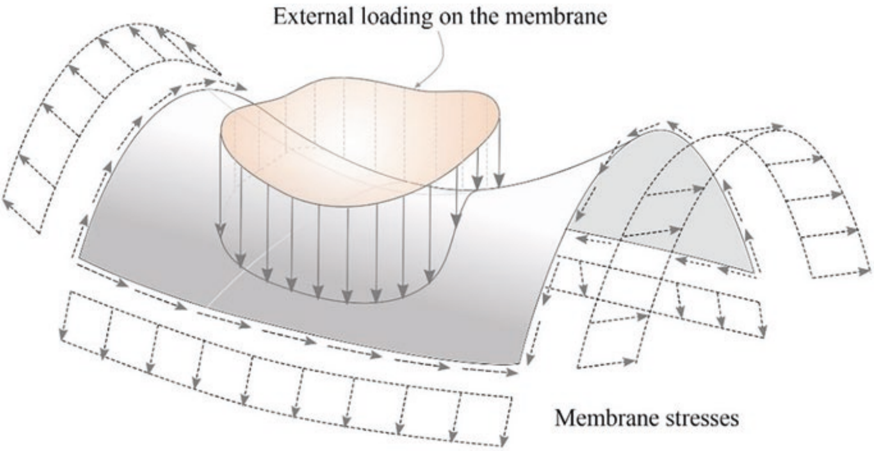

Fig. 2.4 Membrane systems transfer arbitrary loads applying on them as membrane stresses that act along tangent plane to mid-surface of membrane

design of these structures critically relies on understanding the nuances in the implications of these differences.

2.2.2 Boundary-Tensioned Membrane Structures

Boundary-tensioned membrane structures (Fig. 2.5) are prestressed by stretching the membrane elements along its boundaries, which are made of either flexible tension cables or rigid frames/beams.

A fundamental difference between membrane structures and typical civil engineering structures made with concrete, steel, or timber is that the load-carrying capacity of the former arises from curvature or form adaptation. To appreciate how curvature or form adaptation works, it is helpful to understand the concept of constrained minimal surfaces and the weighted catenary mechanism.

Consider a cable or a rope hanging from two support points (Fig. 2.3). The idealized shape attained by a hanging cable or rope under its self-weight falls under the general class of *weighted catenary* [17]. Untensioned cables and ropes form such a curved shape because, unlike beams, their cross-section has negligible bending stiffness. The U-like form adaptation transforms the self-weight into tension in the cable or rope and transfers it to the support as a normal reaction force. It is also worth noting that, due to energy principles, the form of the catenary at equilibrium corresponds to that of least potential energy. This principle applies also in the presence of pre-tensioned state or hanging weights. The deformed state adapts to achieve the equilibrium shape, while the external loadings act as added tension along the structure.

Curvature or form adaptation in membranes works in a similar way, except that the form adaptation is sought by a surface. The curved surfaces formed by membranes under external loads, including the simplest load case of self-weight, fall into the class of constrained *stable minimal surfaces* [18]. It implies that although the

Fig. 2.5 Example of a boundary-tensioned structure: Millenium Dome (O2 Arena), London (left) [16]; McArthurGlen Designer Outlet Village; architecture: Richard Rogers; engineering and fabrication: Buro Happold, Tensys Ltd., Architen Landrell (right)

designers can define the perimeter and support points for the membrane structures as constraints, the form of the structures is bounded by an envelope of limited possibilities, which depend on the design prestress. Thus, the form of a membrane structure has to be found through an iterative approach considering large deformations. This process differs from the technique used for typical concrete, steel, or timber structures, where the designer performs structural analyses under small deformation assumptions.

The process of deriving the form of the tensile elements of membrane structures is known as form-finding. A demonstrative example of form-finding in a membrane art installation is depicted in Fig. 2.6.

Since the structural support system is designed in congruence with the tensile elements of the membrane structure, form-finding plays a pivotal role in the overall structural optimization and weight savings. The geometrically nonlinear response of tensile structures demands reliance on computational simulations and specific

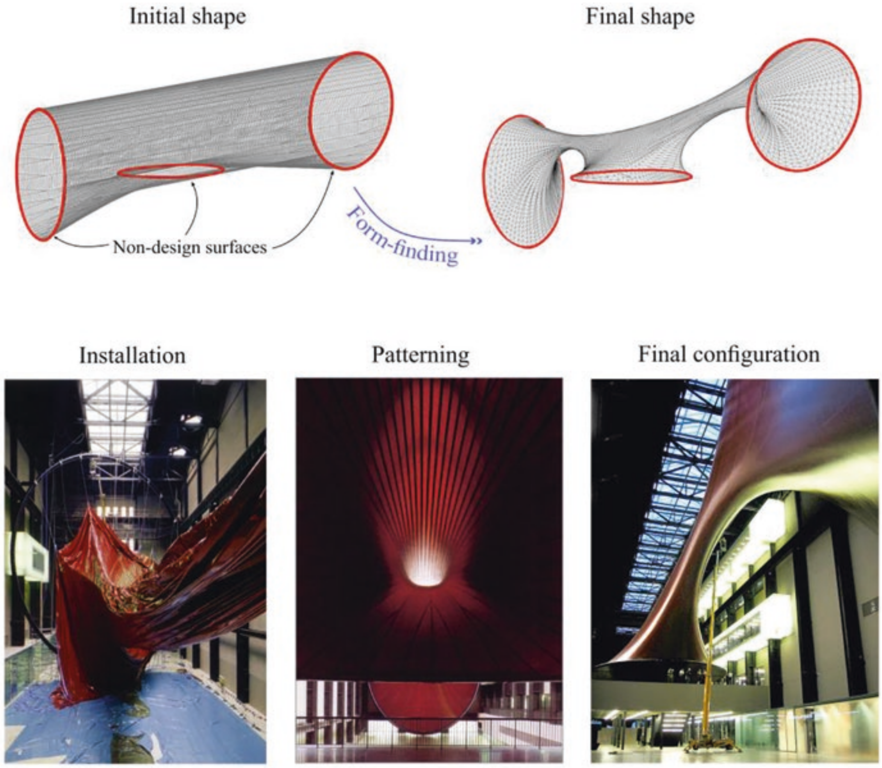

Fig. 2.6 Form-finding and built result of Anish Kapoor's Marsyas. Form-finding technique enables to obtain a final configuration, starting from an initial shape with constraints (top). The realization of the membrane sculpture, showing installation and tensioning, details of the patterning, and the final configuration (bottom). Engineers: Arup; sculpture contractors: Hightex Group, Germany; membrane engineering: Tensys Consultants Ltd.

numerical methods such as transient stiffness method [19], force density method [20], or dynamic relaxation method [21] for form-finding. Physical model-based approaches involving soap-film, fabric, or paper [9, 22] for the derivation of membranes form are also prevalently used for benchmarking the computationally evaluated forms.

An additional process, called patterning, is needed to design and install these structures. Although patterning is uncommon in other construction techniques, it is a necessary step in membrane structural design to determine how the shape obtained through the form-finding process will be realized. In order to perform this step, the membrane design shape must be traced back to an unstressed configuration and then decomposed into flat parts, approximating the 3D shape into bidimensional elements. During installation, the pieces of cut membranes from the raw sheets are joined mechanically or through welding. Once the complete membrane has been tailored, its installation requires careful procedures by skilled operators, so that prestress is gradually applied, and the product handling complies with the material specifications.

2.2.3 Pneumatic Membrane Structures

Pneumatic membrane structures are predominantly used as pressurized cushion-type cladding elements, air beams and façades, as demonstrated in Fig. 2.7. They are also popularly employed for designing inflatable event tents, temporary structures, art and architectural installations, as they offer effective solutions at minimal material weight and cost.

As opposed to boundary-tensioned membrane, pneumatic structures are composed of doubly or multi-layered panels prestressed by an internal inflation pressure. As a result, this structural configuration provides additional stiffness against bending-type loads due to their pressurized nature.

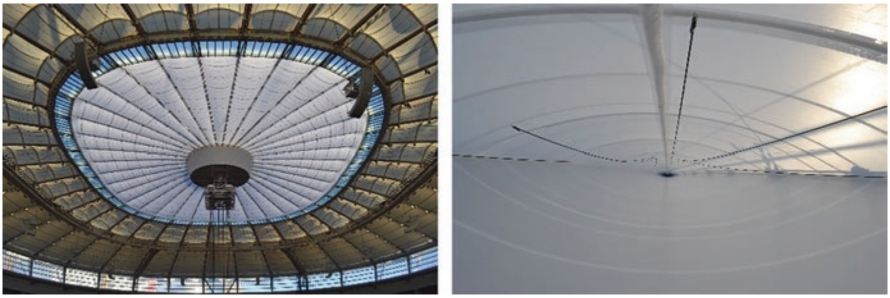

Fig. 2.7 Example of a pneumatic structure with cushion realized in PTFE-coated PTFE weave (left) and internal view of inflated cushion (right). BC Place Stadium, Vancouver, CA (© Christoph Paech/schlaich bergermann partner)

Furthermore, the form-finding process differs in inflated pneumatic membrane structures because the thin sheet's patterning and seams principally dictate their form. A form-finding exercise is usually performed to verify whether the inflated structure's final shape under the prescribed internal pressure is in accordance with the desired form. An adjustment in the design dimensions of the pressurized membrane panels follows by iterating this step until the final inflated shape is satisfactory. As described in boundary-tensioned membranes, the patterning step and complex installation procedure are also performed for pneumatic membranes, where each inflated cushion is patterned individually.

2.2.4 Structural Design Optimization Challenges and Opportunities

Although tension structures are based on an efficient load-carrying mechanism, design improvements could be achieved through an advanced understanding of the behavior of design materials and pertinent optimization techniques during structural design. Such comprehensive approaches could be a powerful tool at the initial, conceptual, and design stages of the membrane structure and can potentially identify efficient design states that are even beyond a design engineer's imagination [23].

Optimization strategies targeting structural geometry, component dimensions, shape, and topology are topics of active research in aerospace, mechanical, and civil engineering disciplines [24, 25]. In recent years, the accelerated advancements in the field of machine learning have influenced novel strategies for structural optimization, such as neural reparameterization [26], neural density representation [27], and Bayesian structural optimization [28]. However, literature on structural optimization methods applied to membrane structures are scarce, indicating the presence of a knowledge gap. Drawing parallels from the aforementioned disciplines, a pursuit to fill this knowledge gap by employing classical and machine learning-driven optimization methods could result in substantial economic and environmental gains by means of further efficient material utilization.

While these structural optimization methods primarily assume elastic response, the materials used in membrane structures do not retain such simple material response throughout their life cycle. The membrane materials undergo phenomena such as yielding, time and temperature-dependent responses, fatigue, and damage, which can severely impact the mechanical performance of the material and that of the overall structure [29, 30]. Therefore, mathematical models that accurately predict the complex responses of the materials used in membrane constructions must be developed as an accessory to computer-aided design and optimization of the overall structure.

2.3 Membrane Materials

To achieve sustainable design solutions through membrane technology and fully exploit its advantages, the structural efficiency described in the previous section must be paired with a detailed understanding of the intrinsic properties and behaviors of the materials used. Membrane materials need to be flexible to achieve an adequate displacement and a pure tensile stress state that complies with the forms imposed by the boundary conditions. Hence, the bending stiffness should be negligible. This is obtained using relatively soft composites or homogeneous materials, whose stiffness is more than one order of magnitude lower than concrete, and of a reduced thickness, generally lower than 1 mm, consequently producing a lightweight solution for the envelope. Membrane structures are currently realized by employing two leading technologies: *fabrics* and *foils*, where the latter is mainly produced with polymers.

2.3.1 Fabrics and Foils

The load-carrying base cloth of woven fabrics is formed from yarns combined in different ways to create a matrix of interlaced threads. The threads are engaged in two orthogonal directions, called warp and weft, through various techniques (two examples of these are displayed in Fig. 2.8). The weaving techniques used to produce the base cloth cause a waviness in the trajectories of the fibers, different in the two planar directions, resulting in technique-dependent material stiffness and nonlinear orthotropic behavior. In most fabrics, the warp direction is stronger and stiffer than the weft one [7].

Textile fabrics are usually coated to protect the base cloth from environmental weathering as well as to ensure the sealing against water and air. The coating layer

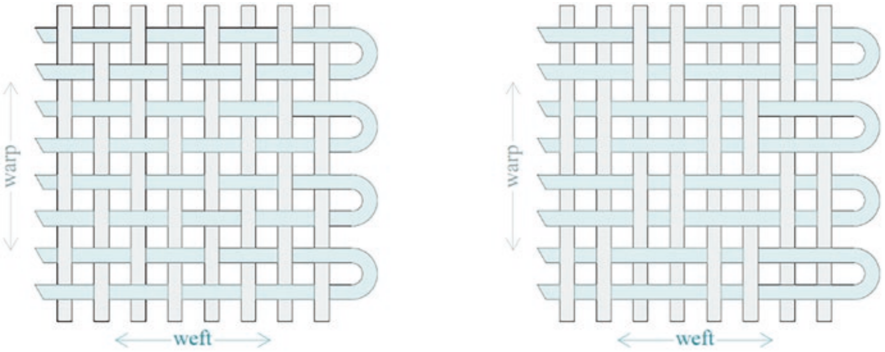

Fig. 2.8 Two most common arrangements of threads in a fabric: plane wave (left) and basket wave (right)

also plays a key role as a structural component, as it enhances the in-plane shear stiffness of the fabric and transfers the stresses between different panels through welded joints. The two most widely used families of woven fabrics are PVC-coated polyester and PTFE-coated glass fibers. Their main differences are the durability, which is around 20–25 years for the former and 30 years for the latter, and the behavior after yield. In fact, PVC-coated polyesters are very flexible and comply with any shape a modern envelope might request. On the contrary, PTFE-coated glass fiber fabric is rather brittle because of the glass material, thus requiring additional care during the installation phase [7].

The category of foils mainly refers to the material ethylene–tetrafluoroethylene (ETFE), a semicrystalline thermoplastic polymer that is extruded to produce a homogeneous foil. The expected lifespan of an ETFE solution is 30 years. ETFE is very similar in its chemical structure to PTFE, indicating high UV resistance, ductility, self-extinguishing properties and a light transmission superior to that of glass. The last property is especially fascinating for architectural applications since the material provides natural light to the interiors of the building, offering a lighter and greener alternative to glass. This results in large weight savings in the envelope and supporting structures, thus reducing the environmental footprint and the energy required for production (~10 times lower than glass) and installation (24–70% less than glass). Lately, researchers are also exploring the possibility of embedding photovoltaic cells during production, with promising results for solar energy collection and the clean energy transition [30].

2.3.2 Thermomechanical Response of Structural Membranes

Membrane materials are highly nonlinear and undergo large deformation. Moreover, the polymeric nature causes their response to be dependent on *temperature* and *time*. High strain rates and low temperatures increase the stiffness and strength, while low strain rates and high temperatures soften the response [31], as illustrated in Fig. 2.9 for ETFE foils as a representative example. More specifically, ETFE membranes are highly sensitive to thermal and deformation rate effects, which only moderately influence the mechanical response of fabrics [32–35]. In fact, from the experimental data reported in Fig. 2.9 and in the literature [34], ETFE experiences an approximate initial stiffness decrease of 35% between 23 °C and 60 °C, and a corresponding yield strength reduction of 40%. For the same temperature range, PVC-coated polyester experiences a stiffness decrease of 20% [36], while the elastic modulus variation is negligible for PTFE-coated glass fabric [37].

The viscous nature of fabrics and foils also results in stress relaxation over time, when a fixed displacement is imposed. This is the case of boundary-tensioned structures, which can lose prestress over time due to this phenomenon [39]. Similarly, the dual condition of constant applied stress realizes a continuous increase of strain over time. Such creep conditions can occur in pneumatic membrane structures,

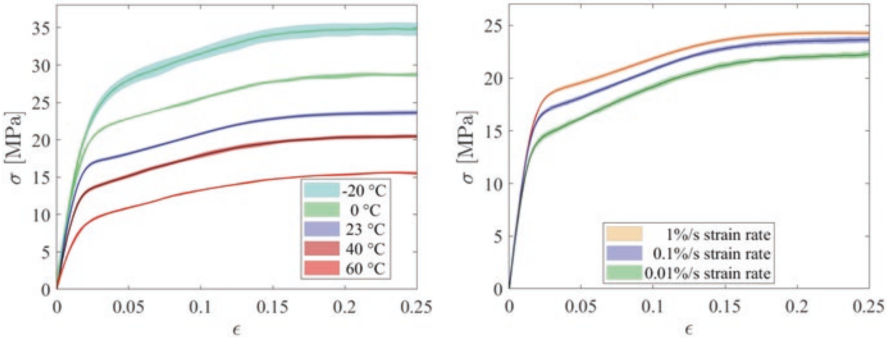

Fig. 2.9 Engineering uniaxial stress-strain curves of ETFE foils, experimentally measured within LIGHTEN project [38]. Response for (left) different temperatures at a constant strain rate of 0.1%/s and (right) for different strain rates at a constant temperature of 23 °C

where the constant inflation pressure generates a stress state dependent on the shape of the cushion. If the material continues to strain due to its viscosity, the shape will change, causing the prestress, and hence the stiffness, to decrease.

2.3.3 Constitutive Modeling Challenges and Opportunities

All the above-mentioned temperature and time effects strongly affect most membrane material responses and must be accounted for, in order to achieve an optimal design. However, these features are rarely considered by designers at present, due to the lack of construction codes for membrane structures [40] and the suggestion to adopt linear elastic models in pre-standard documents [41]. The use of such simplified approaches can result in overdesign, employing unnecessary material, or unsafe design, as reported by Cabello and Bown [42]. The lack of confidence in the available design tools and material models is hindering the use of membrane technology, weakening the impact that tensioned structures could have in reaching sustainable construction practices.

To fully exploit the recognized potential of membrane structures in the environmental cause and the versatility of their applications, comprehensive thermo-visco-elasto-plastic constitutive models must be developed. In particular, the definition of the time and temperature dependence of the mechanical properties and yielding [43] of membrane materials is of great interest among the engineering community [34, 42]. These features also influence the representation of design load cases, whose expressions should include temperature condition and loading velocity. Comprehensive experimental campaigns at multiple conditions represent the stepping stone for the development of accurate material constitutive relations through different modeling strategies, including data-driven approaches, which are part of current research efforts [38].

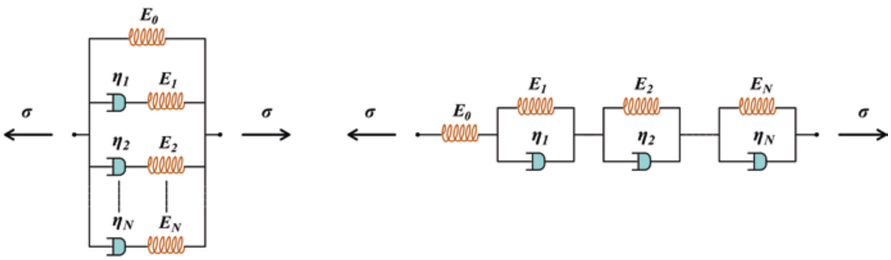

Fig. 2.10 Two celebrated generalized rheological models for viscoelastic materials: Wiechert (left) and Kelvin-Voigt (right)

Examples of constitutive relations capable of overcoming the current linear elastic approaches in order to capture the complex nonlinear and time-dependent membrane viscoelastic response are given by rheological models. They are defined through a combination, in series or parallel, of N linear dashpots of viscosity η_i (i = 1, .., N) and N + 1 springs of stiffness E_i (i = 0, ..., N), as displayed in Fig. 2.10 [44].

For a generalized Kelvin-Voigt model, the time-dependent relationship between strain $\varepsilon(t)$ and stress $\sigma(t)$ can be expressed by defining $D_i = E_i^{-1}$ and $\tau_i = \eta_i/E_i$ and by applying the Boltzmann superposition principle as:

$$\varepsilon\left(t'\right) = \int_0^{t'} D_0 + \sum_{i=1}^{N} D_i \left(1 - e^{-\frac{t'-s}{\tau_i}}\right) \frac{d\sigma(s)}{ds} ds$$

where the term $D_0 = E_0^{-1}$ represents the instantaneous stiffness of the material. Since temperature affects the viscosity of materials, this dependence can be incorporated into the model of thermo-rheologically simple materials through the time-temperature superposition principle. Recent contributions in the literature report some attempts to model membrane materials with rheological models [45, 46]. However, the results for building construction materials are still not sufficiently developed to allow their use in the design of membrane structures [47, 48].

2.4 Sustainability of Membrane Structures

Although common sense would relate polymers to materials with high environmental impact and production cost, these two aspects are less crucial for polymeric membrane structures when compared to traditional constructions. Sustainability of membrane structures is addressed in the following in terms of embodied energy, material consumption, and recyclability.

Table 2.2 Energy required to manufacture the same volume of different materials, normalized by corresponding value for steel [49]

Material	Relative energy per unit volume	Material	Relative energy per unit volume
Steel	1	Polystyrene	0.14
Aluminum	0.68	HDPE	0.10
Nylon	0.23	PVC	0.10
Polycarbonate	0.20	LDPE	0.08
Acrylic	0.19	Polypropylene	0.08

2.4.1 *Embodied Energy and Material Consumption*

The relative energy needed to produce the same volume of different materials is reported in Table 2.2, using the energy consumption data to produce sheets of different materials. The table shows that the manufacturing cost for polymers is less than 25% of that for steel [49].

In particular, the comparison of embodied energy in membranes is more properly referred to a square meter of envelope elements. For example, ETFE elements have an embodied energy that varies between 27 and 210 MJ/m^2 (overestimating the weight to 1 kg/m^2). This value depends on the solution chosen among a single foil or a multi-layered cushion, and the factors considered in the energy calculations [50, 51]. Comparing ETFE to the most common transparent cladding technology in roofs and facades, float glass, a 6 mm thick panel has an embodied energy of 300 MJ/m^2 [50]. The benefit in terms of embodied energy of ETFE solutions would be even higher if the overall structural system is considered, as ETFE enables lighter supporting structures. In this regard, three case studies of transparent roofing construction collected from the literature [52, 53] are displayed in the histogram of Fig. 2.11. For each of them, the weight per unit area is plotted under the hypothesis of using either glass or EFTE as cladding materials. The efficiency of the tensile structure system is evident as it leads to an overall weight saving in the construction, with a reduction of the material consumption varying from 45% to 85% with respect to the corresponding glass roofing installation.

Assessment of further sustainability aspects for ETFE and fabric structures is also available in the literature. In particular, stadium facades and atria roofing designs with tensile structures have been compared to traditional technologies in terms of carbon footprint [54], primary energy consumption [52], or completing a life cycle impact assessment [53]. The consensual conclusion is that structures with membrane elements are more environmental-friendly than traditional constructions.

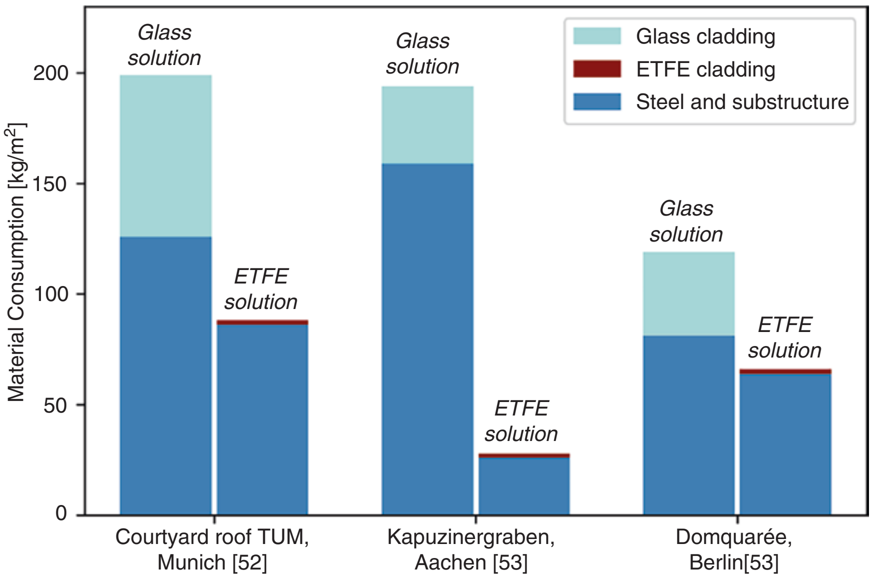

Fig. 2.11 Material consumption comparison between glass and ETFE solutions for transparent roofing for three different case studies [52, 53]

2.4.2 *Recyclability*

In addition to the aspects of low embodied energy and material consumption, the sustainability of tensile structures is further provided by the reuse and recycling of their components, membranes, and substructures. Indeed, an emerging trend is to reuse fabrics that have reached their lifespan, finding a second life in a less demanding environment. Although reusing can represent a meaningful way to reduce the carbon footprint of the membranes, recyclability currently offers more alternatives. In fact, it is well known that thermoplastics lack strong bonds between the polymeric chains, so they can be recycled. ETFE [30] and PVC-coated polyester membranes [55] are eligible for this process and thereby reduce the amount of their embodied energy because some of the production steps necessary for the virgin material can be circumvented during the process of recycling.

Traditional fabric materials are difficult to recycle because the textile composites need to be separated in their components, woven and coating: that is the reason why a textile membrane like PTFE-coated glass is not recycled. Nevertheless, the manufacturers of foils and fabrics are considering recycling options and are committing to more sustainable production. Examples are the Texyloop [55] project of Serge Ferrari on PVC-coated polyester membranes, which aimed to recycle cut-off and unused fabrics to produce new raw materials, and a recent project run by the startup Polyloop [56] that aims to recycle PVC from PVC-composite materials.

Because of its homogeneous nature, the recycling process of ETFE is relatively simple, yet essential in reducing the production of dangerous substances for ozone layer depletion, such as the R11 (trichlorofluoromethane) and R22 (difluorochloromethane) emission during its polymerization [53]. At the current state of the art, the Environmental Product Declarations of the ETFE cushion system of Vector Foiltec, a market leader in ETFE systems design and building [57, 58], reports that the material is recycled, either to produce new foils or to realize other ETFE components such as pipes and valves, mainly used for pneumatic cushions [59]. The recycling of ETFE foil as a new material is indicated to reduce the R11 emission by 47%, while it reduces global energy consumption[1] by 14% [57, 58]. ETFE foil also outperforms glass in the recyclability aspect, since the glass used for buildings is almost non-recyclable because of the difficulties in removing coating layers, and it demonstrates shallow (5%) energy savings [60].

2.4.3 Thermal Properties Challenges and Opportunities

The current major drawback of membrane technology, related to sustainability, is its thermal performance. Although the lightness of the cladding system enables most of the advantages of the solution, the reduced thickness of the membrane materials causes its thermal conductivity to be higher than the traditional building technologies [61]. For example, an ETFE cushion has a thermal transmittance in a range between 2.9 and 1.4 W/m^{2}K, depending on the number of layers [62], while modern glazing systems reach values that range from 2 [61] to 1.1 W/m^{2}K, depending on the surface treatments [63]. Nowadays, ETFE's low thermal performance limits its application in tensile structures mainly to atria, sports halls, stadia roofing, squares, industrial buildings, and other constructions where thermal requirements are not priorities. Several strategies can be adopted to improve and mitigate this drawback, such as the use of multi-layered membrane structures or cushions. These solutions provide additional separation layers from the outer environment and take advantage of the insulation given by the air layer [64]. Moreover, the use of airflow, either natural [65] or generated, toward the surface of the membranes, has been illustrated to improve the energetic performance [66] and has been successfully employed in large-scale projects such as the Khan Shatyr in Astana [67]. Additional improvements can be obtained by using different colors, reflective coatings, and printed patterns, especially on ETFE transparent solutions, to tailor the thermal radiation performances to the specific project demand [30].

---

[1] Considering the sum of the PENRT (total use of non-renewable primary energy resources) and PERT (total use of renewable primary energy resources) indexes of the life cycle assessment [57, 58].

2.5 Conclusions

Membrane structures display great sustainability potential due to an efficient load-bearing mechanism realized through a reduced amount of highly recyclable materials with low embodied energy. The maturity reached in engineering design and material aspects defines this construction type as a promising sustainable solution for a broad range of applications in building engineering, encompassing large-scale facilities, and correspondingly as the opportunity to reduce the impact of the construction industry on our planet and contribute to the goals set by the COP21 Paris Agreement.

Tensile membrane structures have been shown to be a reliable construction technology, with satisfying durability and versatility in adapting to multiple envelope requirements, from small to large scale, across different climates. The latest advancements discussed and the recycling possibilities are expected to anticipate a wider spread of the technology to obtain lighter buildings and more resource-conscious designs in the near future. The main opportunities and challenges to be faced for pursuing the next step forward in membrane structures sustainability have been described at the end of each previous section and include structural design optimization, thermo-visco-elasto-plastic constitutive modeling, material recycling, and thermal properties enhancement. The additional knowledge and the design tools that will result from these research efforts will provide an optimized, safe, and conscious use of the resources for the built environment.

Acknowledgements Financial support from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement 'LIGHTEN - Ultralight membrane structures toward a sustainable environment' H2020-MSCA-ITN-2020-LIGHTEN-956547 is gratefully acknowledged.

References

1. Sustainable Development Goals from United Nation. https://www.un.org/sustainabledevelopment/. Accessed 3 Dec 2022.
2. International Energy Agency and the United Nations Environment Programme. (2018). 2018 Global Status Report: Towards a zero emission, efficient and resilient buildings and construction sector.
3. United Nations. (2021). 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector.
4. George Gastin, Forthbridge, Edinburgh, SCO. https://creativecommons.org/licenses/by-sa/3.0.
5. Felipe Gabaldón, Oceanographic, Valencia ES. https://creativecommons.org/licenses/by/2.0.
6. Drew, P. (1979). *Tensile architecture*. Routledge.
7. Seidel, M. (2009). *Tensile surface structures: A practical guide to cable and membrane construction*. Wiley.
8. Bischoff, M., Ramm, E., & Bieber, S. (2018). *Computational methods for Shell analysis*. IBB-Universität Stuttgart.
9. Hutchinson, J. W. (1966). A survey of some buckling problems, AIAA Jn14, 1505.

10. Barbero, E., & Tomblin, J. (1993). Euler buckling of thin-walled composite columns. *Thin-Walled Structures, 17*(4), 237–258.
11. Ju, G. T., & Kyriakides, S. (1992). Bifurcation and localization instabilities in cylindrical shells under bending—II. Predictions. *International Journal of Solids and Structures, 29*, 1143–1171.
12. Kyriakides, S., & Ju, T. (1992). Bifurcation and localization instabilities in cylindrical shells under bending Part I: Experiments. *International Journal of Solids and Structures, 29*, 1117–1142.
13. Deutsches Institut für Bautechnik, Pfeifer Seil und Hebetechnik Gmbh. (2018). European Technical Assessment ETA-11/0160 PFEIFER Wire Ropes.
14. Williams, C. J. K. (1990). Travelling waves and standing waves on fabric structures. *Structural Engineer, 68*(21), 432.
15. Healey, T. J., Bin, C. Q., & Li, R. (2013). Wrinkling behavior of highly stretched rectangular elastic films via parametric global bifurcation. *Journal of Nonlinear Science, 23*, 777–805.
16. O2 Arena from the Emirates Air Line cable car. cc-by-sa/2.0 – © PAUL FARMER – geograph.org.uk/p/3018490.
17. Osserman, R. (2010). Mathematics of the gateway arch. *Notices of the AMS, 57*(2), 220–229.
18. Meeks, W. H., & Perez, J. (2011). The classical theory of minimal surfaces. *Bulletin of the American Mathematical Society, 48*(3), 325–407.
19. Argyris, J. H., & Scharpf, D. W. (1972). Large deflection analysis of prestressed networks. *Journal of the Structural Division, 98*, 633–654.
20. Schek Heidelberg, H.-J. (1974). The force density method for form finding and computation of general networks. *Computer Methods in Applied Mechanics and Engineering, 3*(1), 115–134.
21. Otter, J. R. H., Cassell, A. C., Hobbs, R. E., & POISSON. (1966). Dynamic relaxation. *Proceedings of the Institution of Civil Engineers, 35*(4), 633–656.
22. Taylor, J. E. (1976). The structure of singularities in soap-bubble-like and soap-film-like minimal surfaces. *Annals of Mathematics, 103*(3), 489–539.
23. He, L., Li, Q., Gilbert, M., Shepherd, P., Rankine, C., Pritchard, T., & Reale, V. (2022). Optimization-driven conceptual design of truss structures in a parametric modelling environment. *Structure, 37*, 469–482.
24. Vanderplaats, G. N. (1982). Structural optimization-past, present, and future. *AIAA Journal, 20*(7), 992–1000.
25. Haftka, R. T., & Gürdal, Z. (2012). *Elements of structural optimization*. Springer Science & Business Media.
26. Hoyer, S., Sohl-Dickstein, J., & Greydanus, S. (2019). *Neural reparameterization improves structural optimization*. http://arxiv.org/abs/1909.04240.
27. Chandrasekhar, A., & Suresh, K. (2021). TOuNN: Topology optimization using neural networks. *Structural and Multidisciplinary Optimization, 63*(3), 1135–1149.
28. Shin, D., Cupertino, A., de Jong, M. H. J., Steeneken, P. G., Bessa, M. A., & Norte, R. A. (2022). Spiderweb Nanomechanical resonators via Bayesian optimization: Inspired by nature and guided by machine learning. *Advanced Materials, 34*, 2106248.
29. Kmet, S., Tomko, M., Soltys, R., Rovnak, M., & Demjan, I. (2019). Complex failure analysis of a cable-roofed stadium structure based on diagnostics and tests. *Engineering Fail Analysis, 103*, 443–461.
30. Hu, J., Chen, W., Zhao, B., & Yang, D. (2017). Buildings with ETFE foils: A review on material properties, architectural performance and structural behavior. *Construction and Building Materials, 131*, 411–422.
31. Ward, I. M., & Sweeney, J. (2012). *An introduction to the mechanical properties of solid polymers* (3rd ed.). Wiley.
32. De Focatiis, D. S. A., & Gubler, L. (2013). Uniaxial deformation and orientation of ethylene-tetrafluoroethylene films. *Polymer Testing, 32*, 1423–1435.
33. Galliot, C., & Luchsinger, R. H. (2011). Uniaxial and biaxial mechanical properties of ETFE foils. *Polymer Testing, 30*, 356–365.

34. Surholt, F., Uhlemann, J., & Stranghöner, N. (2022). Temperature and strain rate effects on the uniaxial tensile behaviour of ETFE foils. *Polymers*. https://doi.org/10.3390/polym14153156
35. Moritz, K. (2007). *ETFE-Folie als tragelement*. PhD dissertation, Technische Universtät Munich.
36. Zhang, Y., Zhang, Q., & Lv, H. (2012). Mechanical properties of polyvinylchloride-coated fabrics processed with precontraint® technology. *Journal of Reinforced Plastics and Composites, 31*, 1670–1684.
37. Zhang, Y., Zhang, Q., Zhou, C., & Zhou, Y. (2010). Mechanical properties of PTFE coated fabrics. *Journal of Reinforced Plastics and Composites, 29*, 3624–3630.
38. LIGHTEN MSCA Project. (2020). www.lighten-itn.eu; https://cordis.europa.eu/project/id/956547. Accessed 1 Dec 2022.
39. Meng, L., & Wu, M. (2016). Study on stress relaxation of membrane structures in the prestress state by considering viscoelastic properties of coated fabrics. *Thin-Walled Structures, 106*, 18–27.
40. Stranghöner, N., Uhlemann, J., Bilginoglu, F., Bletzinger, K.-U., Bögner-Balz, H., Corne, E., Gibson, N., Gosling, P., Houtman, R., Llorens, J., Malinowsky, M., Marion, J.-M., Mollaert, M., Nieger, M., Novati, G., Sahnoune, F., Siemens, P., Stimpfle, B., Tanev, V., & Thomas, J.-C. (2016). *Prospect for European guidance for the structural Design of Tensile Membrane Structures*. Science and Policy Report (SaP-Report).
41. Houtman, R. (2013). *TensiNet European design guide for tensile structures appendix 5: Design recommendations for ETFE foil structures. TensiNet Association.*
42. Cabello, A., & Bown, A. C. (2019). Using a nonlinear thermo-viscoelastic constitutive model for the design and analysis of ETFE structures. In *Proceedings of IASS annual symposia. Vol. 2019. No. 23*. International Association for Shell and Spatial Structures (IASS).
43. Bosi, F., & Pellegrino, S. (2017). Molecular based temperature and strain rate dependent yield criterion for anisotropic elastomeric thin films. *Polymer (Guildf), 125*, 144–153.
44. Brinson, H. F., & Brinson, L. C. (2008). *Polymer engineering science and viscoelasticity: An introduction*. Springer.
45. Bosi, F., & Pellegrino, S. (2018). Nonlinear thermomechanical response and constitutive modeling of viscoelastic polyethylene membranes. *Mechanics of Materials, 117*, 9–21.
46. Li, J., Kwok, K., & Pellegrino, S. (2016). Thermoviscoelastic models for polyethylene thin films. *Mechanics of Time-Dependent Materials, 20*, 13–43.
47. Argyris, J., Is, D., & da Silva, V. (1992). Constitutive modelling and computation of non-linear viscoelastic solids. Part II: Application to Orthotropic PVC-coated fabrics. *Computer Methods in Applied Mechanics and Engineering, 98*, 159–226.
48. Li, Y., & Wu, M. (2015). Uniaxial creep property and viscoelastic–plastic modelling of ethylene tetrafluoroethylene (ETFE) foil. *Mechanics of Time-Dependent Materials, 19*, 21–34.
49. Crawford, R. J., & Martin, P. (1998). *Plastics engineering* (3rd ed.). Elsevier Butterworth-Heinemann.
50. Robinson-Gayle, S., Kolokotroni, M., Cripps, A., & Tanno, S. (2001). ETFE foil cushions in roofs and atria. *Construction and Building Materials, 15*(7), 323–327.
51. Lamnatou, C., Moreno, A., Chemisana, D., Reitsma, F., & Clariá, F. (2018). Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings. *Renewable and Sustainable Energy Reviews, 82*, 2186–2201.
52. Cremers, J. (2013). Energy issues and environmental impact of membrane and foil materials and structures-status quo and future outlook. In *Proceedings of the conference sb13, implementing sustainability—Barriers and chances, Munich, Germany* (pp. 24–26).
53. Maywald, C., & Riesser, F. (2016). Sustainability – The art of modern architecture. In *Procedia engineering* (pp. 238–248). Elsevier Ltd.
54. Finlay, T. C. R. (2021). The carbon footprint of long span structures: Review of the millennium dome and subsequent tensile systems. In *IASS annual symposium 2020/21 and the 7th international conference on spatial structures*.
55. Serge Ferrari. (2020). Corporate Social Responsibility Report 2020.

56. Polyloop startup. https://polyloop.fr/. Accessed 3 Dec 2022.
57. Vector Foiltec, Asahi. (2018). Environmental product declaration – Texlon®-System with Fluon® ETFE FILM.
58. Vector Foiltec, Nowofol Kunststoffprodukte, Dyneon. (2021). Environmental product declaration – Texlon® system.
59. Robinson, L. A. (2004). *Structural Opportunities of ETFE (ethylene tetra fluoro ethylene)*. MSc Thesis, Massachusset Institute of Technology.
60. Achintha, M. (2010). Sustainability of glass in construction. In *Sustainability of construction materials* (pp. 79–104). Elsevier.
61. Flor, J. F., Liu, X., Sun, Y., Beccarelli, P., Chilton, J., & Wu, Y. (2022). Switching daylight: Performance prediction of climate adaptive ETFE foil façades. *Building and Environment, 209*.
62. Poirazis, H., Kragh, M., & Hogg, C. (2009). Energy modelling of ETFE membranes in building applications. In *11th international IBPSA conference, Glasgow, Scotland* (p. 144).
63. Gobain, S. *Thermal performance of glazing systems*. https://www.saint-gobain-glass.co.uk/en-gb/glass-and-thermal-insulation. Accessed 3 Dec 2022.
64. Alongi, A., Angelotti, A., Rizzo, A., & Zanelli, A. (2021). Measuring the thermal resistance of double and triple layer pneumatic cushions for textile architectures. *Architectural Engineering and Design Management, 17*, 334–346.
65. Tian, G., Fan, Y., Wang, H., Peng, K., Zhang, X., & Zheng, H. (2020). Studies on the thermal environment and natural ventilation in the industrial building spaces enclosed by fabric membranes: A case study. *Journal of Building Engineering, 32*, 101651.
66. Suo, H., Angelotti, A., & Zanelli, A. (2015). Thermal-physical behavior and energy performance of air-supported membranes for sports halls: A comparison among traditional and advanced building envelopes. *Energy and Buildings, 109*, 35–46.
67. Vector Foiltec, Khan-Shatyr project. https://www.vector-foiltec.com/projects/khan-shatyr-entertainment-center-megatent/. Accessed 3 Dec 2022.