The TensiNet Symposium “Softening the habitats. Sustainable innovation in minimal mass structures and lightweight architecture” was held in Milan in June 2019.

MATERIALS

According to what has become habitual in the last meetings, the ETFE foil is the subject of most papers related to materials with a greater concern for the solar radiation and extreme temperatures.

J. Cremers showed a new 3D foil based on the shed roof principle (saw-tooth roof) for sun protection (Fig. 1). The advantage of this approach is to block off the energy intensive direct sun light and to let in diffuse sunlight for the daylight quality into the building. This reduces the cooling energy loads and improves the thermal- and visual comfort inside the building. A selective prototype foil with a hemisphere geometry (diameter of 0.02m) on a millimetre scale similar to a bubble wrap foil has been manufactured. The foil has first been printed with a flat printing pattern adjusted to the sun position and the spatially transformed geometry (hemisphere), and then the foil is spatially transformed. This allows to adjust the same geometry by simply varying the printing pattern according to the location. The main application setup of the new 3D foil would be between two foil layers (external and internal), this means that the minimum requirement is a three-layer foil construction.

Whereas the sustainability discourse was dominated by thoughts on material savings and durability, K. Bernert focussed on two other membrane environmentally compatible properties. On the one hand, membrane constructions soften our built environment by their soft skills and on the other hand, membranes are adaptable. Fabric façades for example, are much more than just a textile wrap. The soft forms of a membrane façade are acoustically effective in the cities’ micro climate and, additionally, they can easily be adapted to the user’s changing needs. This adaptability is facilitated by smart properties as new membranes point towards the incorporation of multiple functions such as information systems, acoustic and thermal conditioning, wind protection, filtering or energy harvesting, that is to say the customization of the envelope relative to the climate of the site, solar orientation and building needs (Fig. 2).

Worried about the quality and eco-efficiency of membrane buildings, C. Monticelli applied three eco-efficiency principles aimed to verify the design choices:
1st principle: the comparison between the sum of the perimeters of the membrane modules with respect to the surface covered by the envelope.
2nd principle: the comparison between the weight of the membrane and the weight of the fixing system.
3rd principle: the comparison between the self-weight of the supporting structure of the membrane and the mechanical load.

The first two principles were verified analyzing 13 ETFE envelopes (roofs, façades or both). The results have been significant for optimizing the design but many other aspects and phases of the building life cycle require to be considered too to find the right balance among all of them.

M. Durka introduced a laminated membrane that consists of PVDF films reinforced with glass fibre mesh (called Fluoscrim™), developed to explore additional solutions for permanent architectural membrane structures. Technical issues that were key during the development stage were: ageing under artificial accelerated weathering tests, confectioning the membrane materials using high frequency (HF) welding techniques and biaxial properties of the membrane (Fig. 3). The preliminary test results gave promising information related to the use of Fluoscrim™ in projects where long-term high translucency wide span structures are envisioned. This material is now available for use in tensile architecture projects while some advanced properties are currently being optimized for a standard product offer. One important perspective to Fluoscrim™ material is the ability to be recycled to bring a more sustainable approach on material development for the tensile architecture construction industry.

E. Kriklenko in “Achieving complex bending-active structures from flexible planar sheets. Hybrid structure introducing the use of spacer fabrics in architectural field” presented a new structural system based on the interactive work between tensioned and bended elements equilibrating each other. They are made of soft materials in elastic sheets stressed by active bending. Since all the materials are soft, each element of the system is unstable but, working together, they create a shell rigid enough to bear self-weight and additional loads. This investigation falls within the field of complex bending-active continuous flexible sheet structures, whose principal acting elements are customized flexible sheets (based on spacer fabric) and a system of tensioned membranes, which deform the spacer sheet in a desirable, stable and resistant configuration (Fig. 4). In this way, lightweight customized double curved surfaces easily assembled for multiple uses can be shaped.
E. Clarke started from the possibility of designing the performance of knitted fabrics thanks to computational tools. She introduced a practical and computational trial to produce a knitted shading structure for a pavilion through a preliminary experimental process focussing on the practical knitting technique, in which the geometry and derived properties of a knitted stitch have been examined. She defined a rule to increase the number of stitches per course resulting in diagonal outer edges with a specific slope. Using this rule, three distinct geometric textile modules were defined with the possibility of combining them into different patterns. adapting them to the diverse program of the pavilion and its orientation within the project site. She also examined various structural techniques (Fig. 5).

“Coating of ETFE. Solar shading for architectural applications” was the topic of C. Maywald. He started from the need to enhance the user comfort and reduce cooling loads of the foils used for architectural applications. That’s why he summarized the development of coating and printing on ETFE, as well as the different techniques for solar shading of ETFE cladding systems, including successful examples (Fig. 6).

In order to allow for the quality assessment of these coatings, he also introduced a new test procedure for coated ETFE.

In “Building Integrated Photovoltaic applications with ETFE-Films”, K. Moritz described the design and installation of building integrated photovoltaic modules in combination with transparent structural membranes made of ETFE-films, illustrated by the transparent roof for the parking lot of the waste management services in Munich (Fig. 7). The total area of the roof made of ETFE-film cushions is about 9,600m² and the flexible translucent photovoltaic modules occupy an area if about 3,000m². They are located in the air inflated interior volume of the ETFE-film cushions, safe from external exposures. The lower layer of the cushions is printed with a dot-pattern for shading. The decision for taking ETFE-film cushions for the cladding of the roof, instead of other materials like overhead glass panes, was based on their advantages.

In “Extreme Soft Skins: Multilayered ETFE for challenging environments” N. Jakica presented the optical and thermal characterization of multi-layered ETFE foils performed at the Tex-

Figure 4: Scaled complex bending-active continuous flexible sheet structure model.
Figure 5: Attaching a closed stitch to a closed hardware.
Figure 6: A high reflective cushion system has been implemented with success in “The Avenues Mall”, the largest shopping mall in Kuwait. It is based on a medium opacity ink printed on the inner surface of the uppermost foil in a 7mm hexagonal matrix pattern covering 84% of the foil area.

tilesHUB - the Interdepartmental Research Laboratory at Politecnico di Milano. Studies include ETFE with advanced silk-screen printed coatings and coating patterns for various real case projects in challenging environments, covering both cold and hot extremes. Moreover, she presented an optimization process for improving the performance of ETFE layer compositions to mitigate high environmental stresses, provide optimal indoor comfort and reduce energy demand (Fig. 8). Finally, different ETFE systems implemented in three projects (St. Petersburg, Milan and Manama) were discussed together with possibilities for future improvements.

A. Angelotti compared the heat transfer performance of double layer and triple layer pneumatic cushions, by taking the effective curved geometry of the cushions into account. To this...
purpose, an experimental study on two small vertical samples was performed (Fig. 9). It revealed that going from a single large cavity to two smaller ones almost doubles the overall thermal resistance of the cushion. It was also found that no calculation of thermal resistance of a vertical rectangular cavity is able to effectively portray the actual behaviour of the samples. In the future, new samples will be investigated together with the convection inside the cushions by means of CFD simulations, in order to better understand the air motion.

M. Rychtarikova introduced the audiovisual comfort in shopping streets covered by structural skins by analysing the impact of common glass and ETFE cushion systems on noise levels and sound reverberation (Fig. 10). The research was done using a parametric study to deduce how the height and width influence the acoustic quantities. Three basic street models were tested: (1) a street without any roof, (2) a street with roof made out of ETFE foil and (3) a glazed roof. The theoretical analysis was done in detail per octave band, in order to show the behaviour at low and high frequencies in the rooms separately. It has shown that, in cases where the ceiling is low, the selection of the material has a strong impact on the overall noise level. Furthermore, the positive impact of a ETFE roof structure, has been proven to be a better solution, not only in terms of noise, but mainly in terms of the reverberation time.

**DESIGN**

D. Ströbel summarized three main steps to follow for the design of pneumatic structures. First is the form finding needed to create a feasible surface and based on the extension of the force density approach with additional constraints: chambers, internal pressure, volumes and reinforcements. The second step is the static analysis starting with the definition of the material properties. An internal pressure is fixed and the non-deformed geometry of the patterns can be calculated. If the pneumatically stressed membrane surface is attached to a bending stiff primary structure or combined with mechanically stressed membranes, their interaction has to be considered (Fig. 11). Third step is the patterning, dividing the form in different parts, optimizing the widths and using fast methods for compensation, seam allowances and welding marks. Evaluation of the patterning is also possible.

J-C. Thomas addressed the problem of an inflatable beam subjected to compressive and transverse loads. Inflatable beams are now well established for transverse loads, but the case of the combined axial and transverse loads has received few attention.

The two loads cannot be superimposed because the axial loads modify the stiffness of the beam. So, new formulations for the bending and buckling of inflatable beams subjected to compressive forces were presented. Analytical formulas were proposed taking into account the effect of the internal pressure.

M. Pedersen recalled biomimicry, meaning that it may be useful to examine examples of how the functions of ecosystems have been solved by living organisms. She seeks to create a qualitative complex map for designers and built environment professionals to relate ecosystem services with design strategies and case studies. She concluded that buildings and whole cities, should become active contributors to eco-sociological systems, rather than remaining unresponsive agents of the ecosystem degeneration. She warned however against mimicking aspects of living organisms that produce sustainable innovations without an understanding of the ecological context, because such innovations can easily become simple technological add-ons or substitution materials in conventional buildings (Fig. 12), missing the opportunity of changing the built environment and re-evaluating the nature of the relationship between people, their built environment and ecosystems.
REALIZATIONS

The realizations presented at the Symposium were representative of the state of the art and showed the diversification of applications from stadiums and sport halls to façades and auditoriums, courtyards and fantasies.

Ch. Paech introduced the basic principles of the design of retractable membrane structures, focusing on the detailed knowledge of the material behaviour and structural systems. He stressed the need for a comprehensive design approach spanning from architecture and structure to mechanical and electrical engineering. He illustrated these concepts with recent works by Schlaich Bergermann Partner, such as the retractable cushions of the BC Place Stadium in Vancouver (Fig. 13). It stands out because the retractable part of the roof consists of 36 pneumatic air inflated and pressure-controlled cushions of fluoropolymer coated PTFE fabric. The cushions were chosen instead of a single membrane to assure the all-year use of the stadium under the specific weather conditions of Vancouver. And the material was preferred for its extremely high translucency and excellent performance characteristics, especially in relation to the folding requirements.

One of the most realistic presentations of the Symposium has been: "Cable erection of the Adana stadium suspended roof" by E. Di Muro (Redaelli). The Adana stadium cable net roof is based on the bicycle wheel principle, using cable “spokes” connected to two cable tension rings (one upper & one lower) and one outer steel compression ring (Fig. 14). Due to the convex shape of the radial cables, the interconnecting elements between the upper and lower radial cables are flying masts and diagonals. The stadium has a capacity of 33,000 seats and its roof has a surface area of 24,000m² covered by a double curved prestressed PVC membrane supported by steel arches. The installation process was a challenging operation that required the greatest care and accuracy (Fig. 15). Its description was stellar.

Ph. Lussou was in charge of showing 3 textile envelopes that, in addition to the conventional advantages (translucency, mechanical strength, dimensional stability, durability, ease of fabrication, installation and maintenance), provide comfort and energy efficiency. The Miramas Athletics Stadium (Fig. 16) is the largest indoor athletic hall in France. It benefits from an incomparable luminous atmosphere thanks to the canvas that covers it, diffusing a homogenous light at the heart of the project. This performance is achieved thanks to the use of a double membrane that provides diffused light, blocking sun glare and preventing shadows. The community gym “Julius-Hirsch-Sportzentrum” in Fürth (Fig. 17) has a membrane roof that spans the field and part of the secondary rooms. It is multilayered consisting of an outer membrane as weather protection, an air space varying from 0.5 to 2.5m thick, a thin cover foil as humidity barrier, a thermal insulation, a small 4cm air gap and the inner membrane. It results in a 30% reduction of the electricity demand for artificial lighting when a dimming control is used. The auditorium of the CIRCA area in Auch is wrapped by a double skin system with insulation (Fig. 18). The distance between the two membranes is 250mm and insulation panels made of rock wool (160mm thick, U=0.2W/m². K) are supported by the lower membrane. The advantage of this system is to preserve the aesthetics of the project while providing thermal and acoustic comfort comparable to what is obtained with conventional construction.

A single ETFE triangular cushion for the atrium of the new Lilienthalhaus in Brunswick was presented by B. Stimpfle (Fig. 19). In the initial design a glass roof was intended but its primary steel structure would have been very heavy and would have required a sprinkler system. That is why a lighter and cheaper alternative was chosen. The primary steel structure has been reduced to a perimeter steel frame placed on the concrete structure. The load carrying cables forming the cushion reinforcement are the only steel parts placed upon the atrium (Fig. 20). The cushion is three layered and covers an area of 430m². The upper and lower layers are supported by steel cables so that the maximum foil stress can be safely carried. They are not connected to the ETFE foil, so they can slide avoiding local stress peaks. And the installation has been easier and faster in comparison to the initially planned glass roof.
In his amazing lecture, N. Sidor presented projects with the rhetoric of the sustainability. He stated 10 principles to save the planet:

His understanding of the application of these principles was illustrated with some projects, the most significant of which was the so called Sustainability Pavilion for the 2020 Dubai Expo (Fig. 21).

A great variety of special projects including sculptures and follies was shown by N. Imagawa, self-described as a surgical architect. He assessed them with his "Structural Energy of Material and Space Function" by categorizing, analyzing and summarizing the outcomes of more than 2,500 designs and comparing their efficiency until completion. He described the follies for EXO 90 (Osaka), the Mycal Sanda Pororoca Atrium and Roof Gardens (Sanda 1993), Kenneth Snelson’s tensegrities and the hand crocheted huge net for 80 children (Fig. 22).

The textile façade for the Textil Akademie in Mönchengladbach, Germany, was shown by B. Stimpfle (Fig. 23). It is a pretensioned membrane and cable structure with valley and ridge cables. In order to allow the view from the class rooms to the outside, an open mesh material with 42% opening was chosen. This mesh is coated with silver PTFE, and gives a shiny surface to the project. The cables are the forming and load carrying elements which are vertically spanned along the façade. The development of the façade from the architectural concept to a shape that is suitable for membranes was explained, together with the supporting steel structure attached to the concrete wall, the almost invisible connection details, patterning process and the installation. More information on pages 26 and 27.

R. Canobbio described a difficult job at: "The tailored interior skin of Nuvola, Rome" (Fig. 24). Starting from a cloud (a true free form suspended in the air), a curved steel framework has been defined and enveloped by silicone coated glass-fibre fabric with an acoustic punch pattern to improve the sound absorption. At the request of the architects (M. & D. Fussa) the joints were hidden in order that the surface is perceived as continuous as possible. The way to materialize the arbitrary shape consisted of slicing the cloud and define buildable sections in the yz, zx and xy planes. The final result was described by the speaker as "a cloud in prison".


A. Angeleri showed the Auditorium 1919 Sacmi in Imola, enveloped by ETFE cushions (Fig. 25). The architects Di Fusco and De Rosa with Canobbio Textile Engineering took care of the executive design and construction of the cushions and their structural support. Particular attention was paid to defining the performance requirements of the ETFE cushions, their structural support and connections and the arrangements for the passage of technical systems. In addition, the performance characteristics of the materials was checked, particularly the determination of the thermal transmittance of the ETFE cushions performed by the Politecnico di Milano through the computational simulation "Optical and thermal characterization of a multilayer ETFE".
REFURBISHMENT
The previous TensiNet Symposium 2016 highlighted how membrane structures suit the preservation of architectural heritage requirements. Moving on, the visual and energetic comfort have been evaluated.

In “A tensile screen for the windows of Castello Sforzesco” E. Kolo presented an interdisciplinary methodology for implementing bespoke, low-impact, lightweight structures as additions to historical buildings with the aim of enhancing their performance in terms of visual, lighting and hygrothermal comfort. The study focused on the renovation of Sala delle Asse, one of the most relevant rooms of Castello Sforzesco in Milan. The design task was to produce self-standing vertical screens for the large-scale windows to reduce the amount of sunlight, as well as to block air drafts that bring humidity. The main challenge was the fragility of the context, since the borders of the screens had to be sealed without perforations in the vaulted edges of the windows. Thus, a textile-hybrid structure has been proposed due to its self-standing principle that would not require drilling on the vault (Fig. 26). An experimental campaign started by performing preliminary anemometric measures on the room and by modelling the luminance level based on the definition of the optical properties of the glazing surfaces. These analyses, combined with parametric simulations, gave results on the preferred position and optical requirements of the curtains.

EMERGENCY SHELTERS
Given the growing need of emergency shelters and the adequacy of lightweight structures and soft skins, several papers addressed this issue. However, most did not assume the use for local materials and self-sufficient technology to avoid dependency and business.

D. Ledesma, from the Shelter Research Unit (International Federation of Red Cross and Red Crescent Societies) addressed the issue of anchoring emergency lightweight shelters (Fig. 28). Field tests have been conducted to address the question: ‘what are the major aspects to consider using anchors in the humanitarian sector?’ Influence of soil, weather, type and combination of anchors, installation, orientation, inclination, depth, displacement and price have been measured. An extensive study of anchor usage, practice recommendations with step by step checklists and a handout for humanitarian field practitioners have been provided to identify the best anchoring option for their context of intervention.

S. Viscuso was concerned with providing shelter for progressive reconstruction with the “Multipurpose shelter - Type 2 (T2 MP)” (Fig. 29) designed and prototyped in the European collaborative project S(P)EEDKITS: http://www.textilearchitecture.polimi.it/multipurpose-unit.html. The T2 MP has a a covered area of 48m², and a primary structure made of aluminium tubes with diameter of 35mm and thickness of 3mm. The envelope of the tent is made of three different parts: groundsheet fabric, tent fabric and shade net. The structural analysis revealed the limitations of the T2 MP in terms of compliance with both UNICEF targets and European regulation on temporary structures. So that further studies shall evaluate the use of different materials, (e.g. composite materials for the framework or for connectors), or more resistant aluminium to decrease the weight without losing the required safety.

N. Atawula demonstrated a design proposal for a refugee shelter that can be assembled in a few minutes without technical skills. It is based on a prefabricated “pneumatic sandwich” structure in such a way that a shaped “airbag” can be folded into very small size for storing...
and transporting (Fig. 30). When needed, it can be set up by pumping air inside. The compression of the air and the tension of the envelope can support the structure itself. Lightweight timber panels are added to both sides to strengthen it. The main goal is ease of transport and quick assembly.

E. Teruzzi presented the FlexHab (Fig. 31), an application of MadFlex, a composite material panel with a sandwich-like structure. Thanks to its innovative mechanical features, the panel is flexible, even rollable, on one side and absolutely crushproof on the other. The preliminary analysis of different fields of application has shown the potential of MadFlex addressed to the critical context of disaster management for the construction of emergency shelters because it meets their specific requirements: adaptability to different weather conditions, reversibility, high performance, easy to transport, easy to storage, sustainability, affordability, flexibility and modularity, even though it is not a local material available on site.

**EXPERIMENTAL PROTOTYPES**

A fruitful session of the Symposium was devoted to experimental prototypes, many of which resort to active bending as a procedure to increase structural efficiency.

J. Lienhard addressed in “New hybrids” efficient solutions to respond to the challenges of today’s architecture, discovering new fields of application for membranes. He defined hybrids as “a linkage of two parental systems of dissimilar nature into one coupled system” and highlighted the need for using computational capabilities to design complex geometries in a collaborative environment. He illustrated these concepts with a wide range of special applications, from academic exercises to exhibition pavilions, mobile surfing platforms and roofed motorways (Figs. 32 and 33). Changing the context, A. Rizzo showed the Manta Bay project: an above-ground textile pool composed of a tensioned membrane (PVC thermo-sealed) stabilized with the self weight of the water and held by a thin steel bracket that doesn’t touch the membrane (Fig. 34). It is laid on a composed matchboard floor, an eco-friendly composite material, made with rice husk and virgin polymers. The design maintains the structure to a minimum size and the water always clean. It’s easily used, maintained, installed and dismantled. The result is a shape typical of tensile surfaces never seen before in pools.
C. Mazzola described the “TemporActive Pavilion”, subtitled: “First loop of design and prototyping of an ultra-lightweight temporary architecture”, another realistic presentation with added value, due to the opportunity of checking directly the prototype at the grounds of the University. The “TemporActive Pavilion” is an ultra-lightweight temporary structure consisting of bending active GFRP arches, a restraining system made of stainless steel cables, and an ETFE translucent membrane envelope (Fig. 35). It was observed once again that both, the assembly procedure (Fig. 36) and detailing (Fig. 37), affect the behaviour of the prototype. More information on pages 24 and 25.

M. Ramsgaard dealt with the “Transformative Textile Architecture” research developed by the Centre for Information Technology and Architecture, Copenhagen. CITA is an innovative research centre exploring how the current digital culture impacts on architectural thinking and practice working through the conceptualisation, design and realisation of working prototypes. She mentioned two traditions for textile architecture: tents and lining of interiors (curtains and tapestry), that are part of the architectural scenario (Fig. 38), and looked for new ways to use textiles such as knitted fabrics, spacer fabrics, transmaterialisation, bespoke composite materials, hybrid structures, active bending, textile walls, substrates, sensors and, once again, the Hybrid Tower Project and the Isoropia (2018 Venice Biennale Pavilion).

J. Knippers was worried about the current separation between design and construction through a linear organization that affects significantly the research development. Instead, Nature bases its design and construction principles on heterogeneity, adaptability, redundancy and multi-functionality. That’s why he opted for the integration of all the actors involved, as a procedure to increase productivity, illustrated by the BUGA Fibre Pavilion, Bundesgartenschau, Heilbronn 2019. He demonstrated how combining cutting-edge computational technologies with constructional principles found in Nature enables the development of truly novel and genuinely digital building systems (Fig. 39). More information at: https://icd.uni-stuttgart.de/?p=22271.

T. Liddell in “Tension-actuated textiles for architectural applications” showed how dynamic 3D surface geometries may be generated by printing rigid 2D patterns onto pre-stretched fabric (Fig. 40). The resulting surfaces have aesthetic and structural properties similar to adaptable skins found in nature and, if scaled up, could bring a new degree of softness and adaptability to the built environment. They exhibit complex double-curvature and the final shapes are affected by the material elasticity, bending resistance and ambient temperature. Although the principal factor is the initial 2D print-pattern itself, in which small variations result in different surface curvatures. The link between 2D-input and 3D-output geometry has been explored and several designs developed with performative qualities such as incidental bending and snap-buckling. The proposed shape-making technique is among the few fabrication techniques capable of generating complex surface curvature without the need for moulds, formwork or manual labour.

**RESOURCES AND EDUCATION**

M. Tamke introduced the InnoChain ETN network (www.innochain.net), a shared research training environment that examines how advances in digital design tools challenge building culture enabling sustainable, informed and materially smart design solutions. The network aimed to train a new generation of interdisciplinary researchers with a strong industry focus that can effect real changes in the way we think, design and build our physical environment.

R. Roithmayr approached the teaching of membrane architecture based on the Master’s Program for “Tensile Membrane Structures” taught in the Danube University, Krems, (https://www.formfinder.at/masters-program/) and the “formfinder” database/communication platform and glossary that includes case studies, products, experts, companies, impressions, map and types, available at https://membrane.online and https://www.formfinder.at/glossary-tag/ (both consultable with formfinder login).

The Working Group 18 “Environmentally Compatible Structures” of the IASS was represented by P. Vegh. Its mission is to cover the basic theoretical design problems associated with Environmentally Compatible Structures (ECS): “All buildings, structures, infrastructures, reconstructions, their use, materials and connected technologies, which minimize their environmental impact or contribution to outdoor and indoor environmental pollution during the whole life-span of the structure”. https://iass-structures.org/WG18-Public

**OTHER ACTIVITIES**

Apart from the reported lectures, three other sessions were held in parallel:
- Design and simulation of soft structures;
- Performances and reliability of soft materials and
- Soft skins for the built environment for which the author refers to the proceedings available at the TensiNet website.

Other activities offered during the Symposium included the exhibition “In. tension”, focused on the current changes in the field of tensile architecture and experimental prototypes scattered all around the campus, (especially the TemporActive Pavilion), the Open Talk, the TensiNet Partner Meeting, and, of course, the sumptuous conference dinner served at the Castello Sforzesco.