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ELLIPSOIDAL SHAPE AND DAYLIGHTING CONTROL FOR THE ETFE PNEUMATIC ENVELOPE OF A WINTER GARDEN

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Summary. The paper aims to highlight the design and building processes and the interface between the different disciplines, during the design of the pneumatic envelope of the Winter Garden in Verona. Especially the step between the executive design and the structural design of the elipsoidal shape, made of etfe cushions, and the surface characterization and strategy in order to control the solar radiation, in terms of environmental building design.

1. INTRODUCTION

From the initial use on projects such as botanical gardens, zoos, swimming pools, and exhibitions spaces, the ETFE pneumatic technology is now increasingly chosen as envelope design in more traditional buildings for permanent uses and where people spend many hours of the day, i.e. roofing for courtyards, shopping malls, atria and stores. It is more and more used in different climatic conditions, till extreme conditions. Such cases in the Southern Europe, where the solar radiation is intensive for most of the year, exist. Its popularity is mainly due to the daylight transmittance and because of the possibility to generate special shapes. The cushions provide thermal insulation, but are quite totally transparent to long wave radiation. It shows an incomparable transparency equal to 90-95% of the total light and 83-88% of the ultraviolet light, resulting comparable to day light and a marked greenhouse effect (related to high absorption in the infra-red range). Depending on the building use, its design, the site, and the geographical location, some design strategies have to be studied to balance the overheating and the indoor comfort.

ETFE offers a valid alternative to glazing in building envelopes. In comparison to equivalent glazing, pneumatic cushions achieve a comparable level of performance with less than 1% of the weight. This reduces the amount of secondary structure required to support the building envelope with consequent benefits on the primary structure and the foundations allowing unsupported spans up to 10m[1,2]. The potentialities of ETFE overtake the traditional idea of a static building envelope and allow a new type of building envelope which acts as an adaptive filter able to optimise the interaction between the internal ambient and the surrounding environment that can control the light transmission and heat transfer of the cushions. Since the first applications dating back some 30 years ago, born as a technological material mainly from agriculture to architecture, shows an evolution in the treatment strategies of the transparency to sunlight, related to the function of the structure and its location. The main optical limit of the material is represented by the level of distortion, related to the final foil curvature, and by the relatively high diffusion (1.5-3%), which results in a slightly milky view through the building element. However, this characteristic turns into a disadvantage in regions of high sun radiation where providing shading elements is necessary. The use of totally transparent ETFE films for the construction of indoor structures with a comfortable winter climate in cold areas (i.e. Mangrove House in the Arnhem Zoo, Netherlands, 1982 Eden Project, Cornwell, UK, Grimshaw & Partners, 1996) looking for modulation of the intensity of solar radiation through some technological strategies: *a.* the use of printing on film by corona treatment and pigmentation with aluminum powders (with different possible intensity); it allows to print geometric shapes that slightly dull the film and partially reduce the intensity of the incoming solar radiation, in order to optimize the bright and thermal comfort inside, especially in summer and in hot climates (Art center for the college of design, Pasadena, USA, D. Genik Architects, 2004; Duxford Visitors Centre, Duxford, UK, HOK International, 2005); *b.* the use of color in the mixture of the base material granules, the variation of glossiness, the density and the number of layers are strategies that allow modular infinitely the optical and thermal properties of the cushions (i.e. Water Cube, Beijing, China, 2003-2008, C. Bosse, R, Leslie-Carter); *c.* the light transmitted from the ETFE envelope can be decreased through the multilayer cushions manufacturing, by combining different frit patterns printed on the layers which can be moved by changing the air pressure of the chambers[3] : the upper and middle layers are printed in a way that blocks the solar radiation when the two layers are overlapped, by modifying the solar radiation and the brightness inside the considered areas[4] (i.e. Cyclebowl, Hanover, Germany, Atelier Bruckner, 2000; Festo technology center, Esslingen, Germany, Jaschek & Partner, 2000; Kingsdale school, Dulwich, London, de Rijke Marsh Morgan Architects, 2004; The Mall Athens, Greece, Maroussi, Ergotex, 2005); *d.* in a less integrated way, but opposite, some embodiments consider on the inner side the installation of additional shielding systems, such as roller blinds, adjustable brise soleil or opaque panels (i.e. DBU Conference and Exhibition Pavilion, Osnabrück, Germany, 2002, Herzog and Partners). Some recent trends provide for the manufacturing of the cushions also different levels of film transparency with respect to the orientation of the North-South, by leaving transparent areas in the north oriented cushions, ensuring the brightness and the perception of the outside, and dulling with a milky color the areas facing south, in order to reduce or block the UV rays and IR, dampening overheating the effect. (Shopping centre project, Portugal, Promontorio architects - the foils are printed depending on their orientation with respect to the sun, half the cushion is transparent ETFE that faces north allowing sun penetration while the other half, made from white ETFE, is facing south to block sun radiation[5].

The issues related to thermal insulation and solar radiation control in certain times of the year are always to be considered in the design phase. The pneumatic cushions behavior to solar radiation is complex and is the subject of scientific studies; there is still no legislation on this matter, unless documentation resulting from an experimental and often empirical approach.

2. AIM OF THE PAPER

The paper focuses, in a first part, on the review of the state of the art on the available data on the thermal performance of ETFE cushions, then on an overview of the state of the art information on the subject, and, in a second part, illustrates the case study of the multipurpose dome-shaped building, at the Forum Hotel in Verona, designed by Mario Bellini Associati, where the transparent ETFE pneumatic system was chosen as the covering of a multifunctional space for a facility. The objective of this paper is to highlight the decision-making process and the continued mediation within the phases of the executive project related to, on the one hand, to the definition of the technical and structural details for the building envelope and, on the other hand , to design strategies related to the ETFE as facade material, required in order to balance the indoor comfort and the daylighting and to avoid the overheating of the indoor air.

3. INDOOR THERMAL COMFORT IN STRUCTURES COVERED WITH ETFE

It turns up in the field of membranes for architecture the need to understand thoroughly the ETFE thermal and optical properties of the pneumatic systems and, consequently, to have technical information supporting the design on strategies for shading and screening of the transparency. The thermal properties of a building are an important consideration, they impact on the thermal performances and ultimately to the energy cost of the building. A well insulated building will be both easier to heat and easier to cool than a badly insulated building. The U value is an index measuring the heat flux through an element per unit of surface area and temperature difference[6].

Thermal performance is an important factor when dealing with materials of minimum thickness of 0.1-2mm such as ETFE foils as they can't provide appropriate thermal resistance. Although ETFE does not offer exceptional thermal insulating properties, the use of multilayer solutions allows the achievement of considerable values of thermal insulation, comparable with those obtained by means of glazed envelopes, reducing overheating, internal condensation and the energy required for air conditioning, both during summer and winter[2]. Energy strategies to increase the thermal insulation are applied since many years: - by multiplying the ETFE layer (the intermediate pretensioned ones do not assume a structural function in the cushion, but divide the volume of the air in two chambers connected, thereby improving the thermal insulation), - by inserting ETFE layers with shielding printings on the other hand, - besides focusing on the manufacturing of aluminum frames with thermal break profiles, which are clamping profiles usually consisting of several thermally separated parts[7]. If the upper and lower layer are fixed independently one from the other on the primary structure, without welding, the U value can be improved of about 20% [8,9,10].

As declared by Knippers, there are two aspects affecting the value of heat transmission. The first is the surface resistance of air/material interfaces which can be controlled by the number of layers and chambers. Each additional layers of material reduces the volume and provides two more surface resistances (air/membrane/air) which improve the thermal resistivity of the system. The second is the convection effects within the cushion caused by the rising warmer air. These effects depend on the cushion orientation and the direction of heat flow whether horizontal or vertical.

In two studies regarding the application of ETFE cushions as transparent cover for areas between buildings or atriums, it has been deepened the thermal insulation aspect of the system[11,12]: "*An ETFE foil roof will have a better rating for insulation, U value at 1.9 W/m^{2}K (horizontal) in comparison to single glazing at 6.3 W/m^{2}K (horizontal) and double glazing 3.2 W/m^{2}K (horizontal)*". Thermal transmittance U values of ETFE cushions in the literature are resulting from calculations according to DIN 4108 standard and how U value measure has been carried out for 2, 3, 4, 5 layers cushions (U-value = 2.95 – 1.96 – 1.47 – 1.18 W/m²K)[6, 13]. The methods used to determine the thermal transmittance value can be the following: - in accordance with DIN 4108, - finite element calculation of the thermal transmittance of the film and the cushion - empirical analysis in the Hotbox climate chamber of the U value for ETFE pneumatic cushions[14]. It has to be considered that the convective motion of the heat in the chambers, among the different layers influences the thermal performance of the cushions and the estimation of the U value is generally complex.

The great difference between a cover or a façade with ETFE cushions, compared to a glass one is in the ratio between the area covered by a cushion and the length of the aluminum frame: for a ETFE system, the ratio is about 0,8 compared to that of the glass which is about 2. This means that the surface area obtainable with an ETFE cushion corresponds to four or more windows in glass with a reduction of the frames and of the discontinuity frame-glass, with higher homogeneity of thermal transmittance for the same surface.

Besides the thermal insulation control of the building in the evaluation of the thermal performances of the transparency of the ETFE, the thermal effect generated by the passage of the radiation of the solar spectrum from the outside towards the inside, and in particular, the long radiation of the electromagnetic spectrum solar, in order not to underestimate or approximate evaluations. The issue is complex and completely open in the field of scientific research there aren't any software available that consider in the calculation of the thermal performance of the interior of a building the long radiation transmission in the electromagnetic spectrum of the solar radiation (IR) through layers of thin film. A reference in literature, explaining many aspects, but not fully answering the complexity of the matter, is Poirazis et alii (2009)[14]: ETFE is not opaque to the long radiation of the solar spectrum, therefore, in the design phase it is necessary to pay attention to this aspect; it is not possible to treat such materials and the system as a normal glass even if they are normally considered in the simulations of calculation equal to parallel glass sheets.

	U-value (W/m^{2}K)	g-value
6mm monolithic glass	5.9	0.95
6-12-6 Double Glazing Unit (DGU)	2.8	0.83
6-12-6 High Performance Double Glazing Unit (DGU)	2.0	0.35
2 Layer ETFE Cushion	2.9	0.71-0.22 (with frit)
3 Layer ETFE Cushion	1.9	0.71-0.22 (with frit)
4 Layer ETFE Cushion	1.4	0.71-0.22 (with frit)

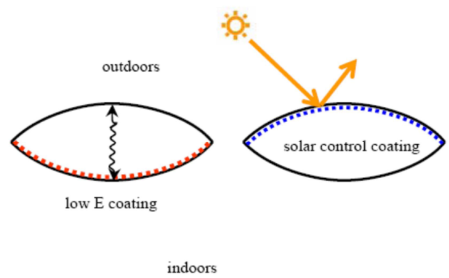

Figure 1: Comparison of glass/ etfe U and G values and thermal behavior of coated or fritted cushions[14]

The thermal and optical properties of ETFE cushions can be changed significantly by the application of coating, prints and shapes. The application of coating films can determine the following behavior: a. low-emissivity coating for the reduction of transmission losses of long waves, i.e. to provide during a cold winter's night a reduction of the thermal transmittance; b. a coating for solar control to reduce the transmission of the electromagnetic spectrum.

Compared with glass, virtually opaque to long radiation, ETFE transmits instead a part of this, which has a great influence on the transmission of the energy absorbed in the layers. The relevance of these effects can vary greatly depending on the environmental conditions and the characteristics of the cushion system built. There are many parameters that affect the transmission of long waves, including the temperature of the floor inside, the radiant temperature of the sky, therefore the difference of temperature, the exchange of long waves, the environment around the building (with or without buildings) .

The issue is currently treated very empirically, by printing on ETFE film, as shading and shielding of the transmission of solar energy in the internal space, which improves the thermal insulation in winter and reduces the amount of waves that enter into the inner space in summer, reducing the risk of overheating the interior space. The value of solar factor G (indicator of the level of transmission of UV and IR rays transmitted) of the ETFE cushions system can be reduced to 0.48 by means of a printed surface and to a minimum of 0.35 using a system of three printed layers[14]. Furthermore it is highlighted in which way the geometry of the printing impinges on the optical properties and transmission of solar radiation, and also how in the printed parts, the intensity of the printing ink affects the transmission, which means that by increasing the intensity it is reduced the transmission of solar radiation[15,16].

4. WINTER GARDEN PROJECT, VERONA, ITALY

Verona Forum (2005-2011), a construction of the side overlooking the street in a compact manner, is a multipurpose complex at the avant-garde as regards solutions for safeguarding the environment. It is also a pioneering design in terms of the technological solutions which control building automation, managing the building so as to increase energy efficiency. Into the complex the Winter Garden structure is one of the first Italian case of an entire envelope, a complete building fulfilled with multilayered ETFE cushions. The translucent building is a charming special structure, which serves the nearly Crowne Plaza Hotel for meetings or just as relaxing area. The Winter Garden has an ellipsoidal form and the 3D curved envelope surface. At one end of the egg-shape, a cubical installation building for technical plants is foreseen, intersecting the ellipsoidal volume. At the opposite end of the egg shape is an entrance area, which should receive a vertical facade.

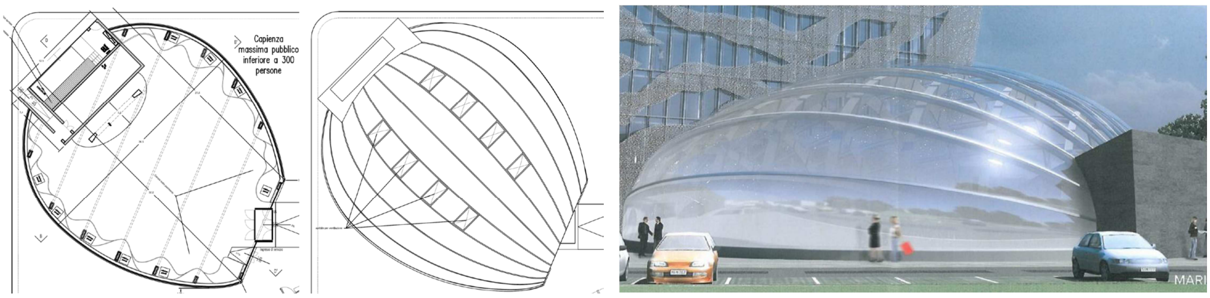

Figure 2: Plants and render of the shape of the Winter Garden in Verona (Source: MBA)

3.1. Executive Design Phase and Engineering Aspects

This case study allows to understand the continuous feedbacks between different disciplines, different building process actors and the steps of the design phase, the executive ones and the engineering process in order to define and build up the elipsoidal shape, made of etfe cushions, and to characterize the surface and the strategy in order to control the solar radiation, in terms of environmental building design.

3.1.1 Structural Design and Analysis

The primary structure of Verona Winter Garden consists of 7 transversal arches, which are hinge connected to concrete foundations. All arches have different shapes to generate the volume of a partial egg. The 7 arches are connected with 11 longitudinal profiles. These profiles are curved, bending stiff, run above the arches and connect all arches to the technical installation building. The steel profiles act also as bearing profiles for ET-foil cushions. The pressure stabilizes the cushions and forms the transparent envelope of the building. This structural system allowed avoiding diagonal bracing, which would interfere the view from inside. The distance between arches, e = 4.50 m., max. arches span is l = 27.1m and the covered area is approximately 625 m².

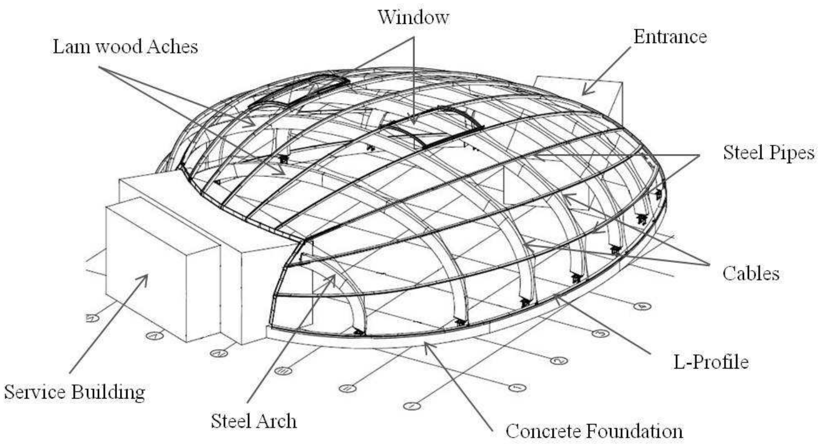

Figure 3: 3D-Model of Verona Winter Garden (Source: Form-TL)

The timber wood 7 arches have a rectangular section 240x800mm product according to UNI EN 14080 and DIN 1052, belong to the class of H GL28 resistance according to EN 1194, whose function is to transmit the self-weight and the external loads of the covering to the reinforced concrete foundation. The 11 horizontal or inclined longitudinal profiles structures consist of tubular circular (diameter 168.3 mm) calendared in steel type S 355 J2. These elements have the function of supporting the loads acting, transmitting them to other structural parts connected to them. The profiles have a longitudinal plate welded perpendicularly to the covering membrane (ETFE), where the cushion is connected by the use of aluminum profiles. The distance among the profiles varies and follows the "shell" shape characteristic of the building.

The steel arches with rectangular section, placed at both ends of the structure, are made up of S 355 J2 steel type elements with rectangular section 200x800mm (semi-arch towards the technical building) and a rectangular section of 200x400mm (side of the vertical glass wall with the entrance). The steel arches have the function to transmit the self-weight and the external loads of the covering to the reinforced concrete foundations.

Regarding the closure structure, the Cushions are foreseen as 4-layer cushions with 250μm, 100μm, 100μm and 250μm foil thickness with minimum and maximum volumes of V_{min} = 18.7 and V_{max} = 33.7m³, respectively. To stabilize the foil cushions against external loads, the cushions receive overpressure against the environmental atmosphere. This overpressure needs to be continuously provided and needs to be modified according to the external load exposure. To reduce the thickness of the cushions, a steel cable is applied above the wood arches to reduce the sag of the foil. The connection detail of the foil along the cushion edge is very unique, which is invisible from outside. From outside, the connection detail is only 10mm thick. Therefore, no plates are visible. The 3m x 4.7m windows are very special being covered with an ETFE cushion, without bracing structure inside the window and a 3d-shaped frame to suit the surface condition of the structure. Minimum frame extension of height above the regular roof surface was possible. The permanent overpressures outside and inside chambers are 300 and 30 Pa, respectively. The winter time overpressure is 600 Pa and the snow overpressure is 800 Pa. Foil Surface area is approx. 3600 m², the surface of 1 ET-foil Layer is approx. 900 m² and the cushion volume is approx. 300 m³. The snow load is qsk Ce = 1.00 kN/m² and the wind base pressure is p = qb Ce Cp Cd = 0.70 kN/m.

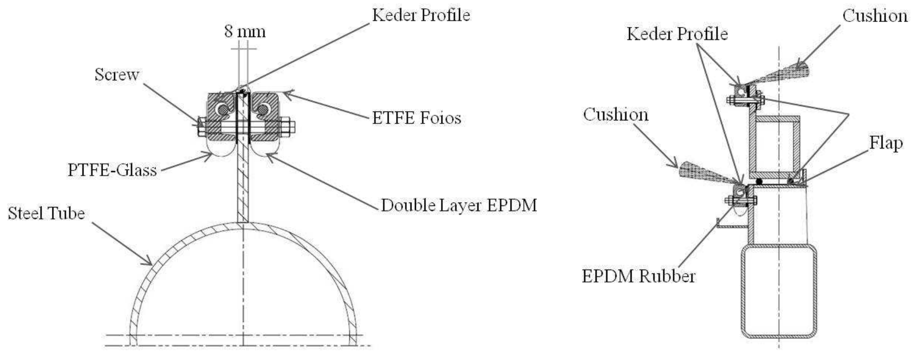

Figure 4: Clamping Profile Detail (Left)and Window Section (right) (Form-TL)

3.1.2 Day lighting Control Strategies

A study on different patterns and layers in order to reach the best results modulating the shadowing and trasparency was undertaken by Canobbio in collaboration with Politecnico di Milano in order to satisfy the requirements and diffuse different lighting rates ensuring the summer thermal comfort, by varying the opacity of the cushions over the whole building. The supplier of the pneumatic envelope, Canobbio company, has undertaken the executive design of the structure finding the right solution for the requirements. The design requirements related to the ETFE pneumatic cushions structure designed for the Winter Garden in Verona were: *a.* by the designers of MBA, to have the first 3m of vertical envelope almost totally opaque to the outside and reach the almost total transparency in the center cushions (at about 6 m from the ground), generating a gradient effect from opaque to transparent starting from the first lower cushion to the top central cushion; *b.* by plant engineers verify that the pneumatic system meets some standard requirements related to the U-value of thermal transmittance and G solar factor value which means a U value = 1.5 W/m^{2}K, and G diffuse value = 0.3. To have an average diffuse value of 0.3, the G value must be from 0.38 to 0.22. We assume a cushion system with 4 layers and printing on all cushions. To meet also the formal requirements of the designer, printing varies in intensity from the opaque part to the transparent and moreover, it is applied in a different way from cushion to cushion.

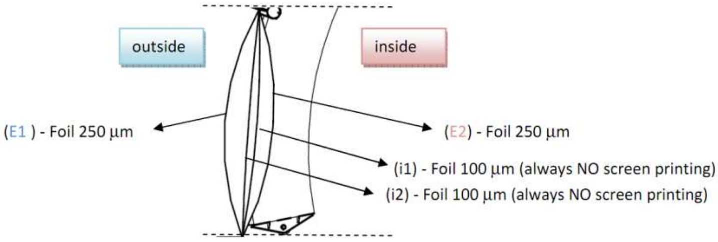

Figure 5: Thicknesses of the four etfe foils (Source: Canobbio)

Printing have been foreseen on the more resistant layer, therefore in the outer one, for all six cushions, and in the internal one for the first two with double printing; due to technical reasons of the printing company the printing was possible only on a layer thickness of 250 μm. The geometry and the percentage of opaque/transparent were also optimized, by choosing geometries in the catalog of the printing company.

The compositional aspect of the project has great potential given by the technical solutions and the materials with a high degree of innovation, however, some limitations emerge in the pneumatic roofing system in the way it has been designed: *a.* the hemispherical synclastic shape it is difficult to verify from a physical-technical and an environmental well-being point of view; *b.* from a formal point of view, this hypothesis answered well to the blending requirements given by the project, but, from the inner environmental wellbeing point of view, this solution did not appear to be the best. Typically for horizontal closed structures with transparent materials it is advisable to apply shading systems and shielding, to reduce the amount of heat coming through; in the specific case it would be therefore desirable to have the greatest shading in the highest part, zenithal to solar radiation. Considering also that the hot air generates an upward movement, it is assumed that extreme conditions in summer a slight overheating of the high part may occur.

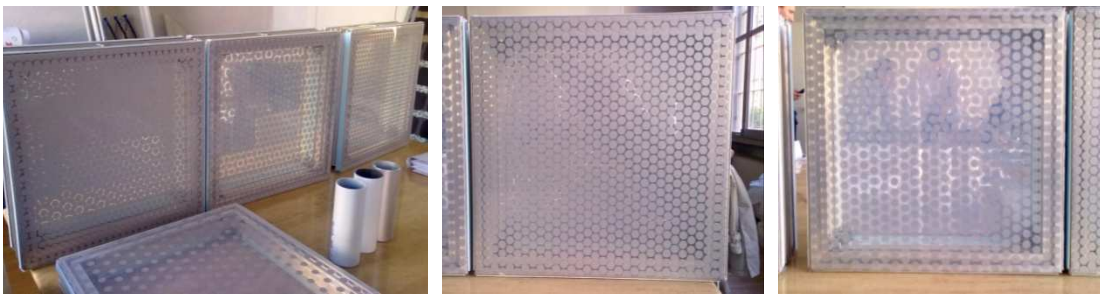

Figure 6: Sample models of the real effect of the overlapped and fritted foils (Source: Monticelli).

Given the considerations and the limits to the designers, a new hypothesis for the transparency of the structure, by inverting the more opaque part with the more transparent one, creating the most dense and opaque prints in the upper cushions, shading towards the lower part, with the fewest at the base. Due to the designers' request, this hypothesis had to be checked by the creation of small cushion models of cushion on 50x50cm frames (fig. 6).Thanks to the evaluation of the mock up, which have significantly given the idea of the final result according to the design requirements, designers have defined a new sequence printing, which better fits the physical-technical requirements for an internal well-being . The geometry which considered a greater transparency with respect to the others (30% opacity) was excluded and have been differently distributed and overlapped to the other geometries.

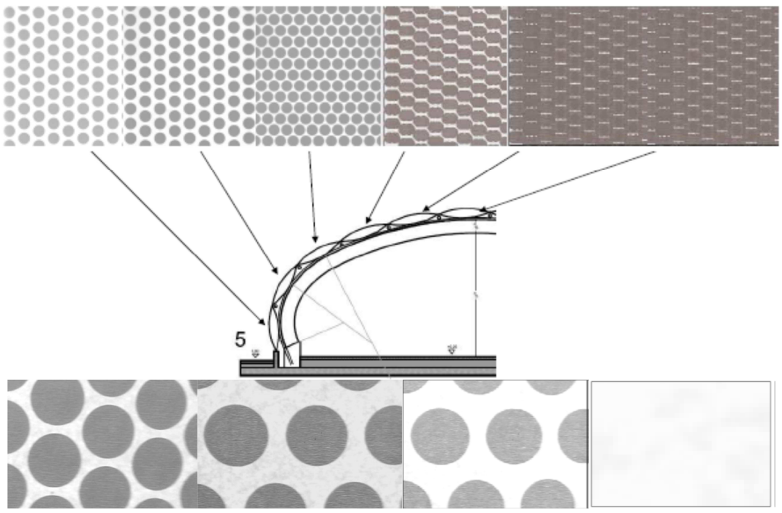

Figure 7: Final sequence of the intensity effect of the screen printing foils and their densities: 70% dark, 50% dark, 50% light and no screen printing (Source: Monticelli, FormTL).

3.1.3 Patterning Aspects

During the engineering phase before the production, cutting patterns were generated with WINNETZ. The distribution of seams was arranged to be in general parallel to the Wood girders.

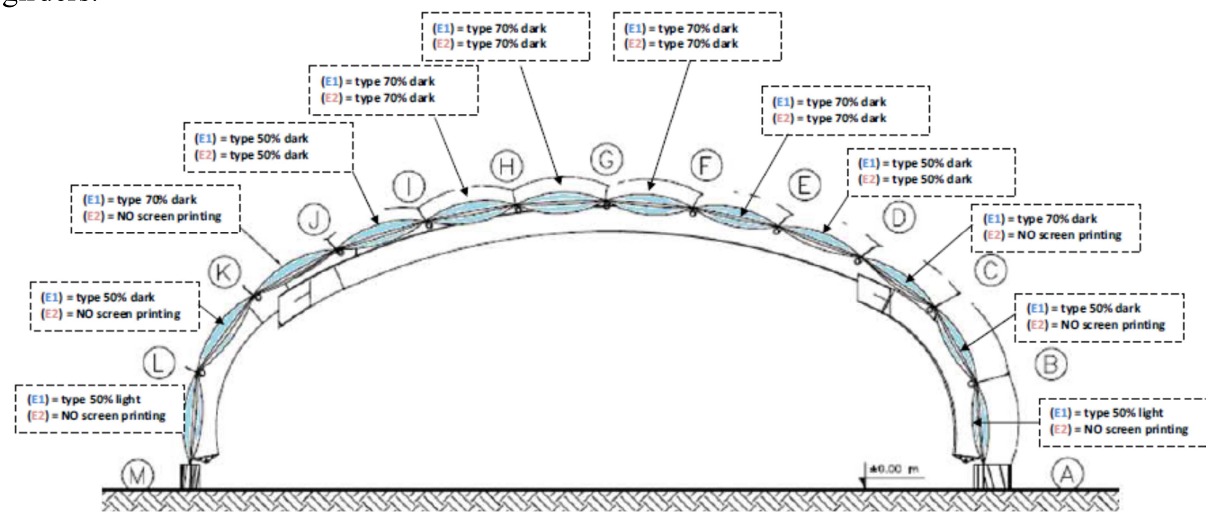

Figure 8: Layout of screen printing density (Source: Canobbio)

All seams in the 4 layers end at the same position to provide a most harmonic view from inside and outside. Based on the targeted visual impact given by the architect (fig. 7,8), the printing schemes of ETFE external and internal layers that determined the pigments density had to be specified for each panel after the generation of cutting patterns for supplying the manufacturing data (fig.8).

3.1.4 Management phase of the ETFE pneumatic envelope

The pressurization system for ETFE cushions inflating, placed in technical building joint to the structure in object, consists of two fans with dehumidification function, to pre-dry the outside air and prevent the formation within the cushion of condensation or algae. Among the various cushions there are communication systems to allow the air to move from one to the other and ensure the same static pressure to the whole. The machine produces two different pressures, one for the inside of the cushion (volume A 330 Pa) and one for the other two more external rooms (volume B 300 Pa). From the machine there are two pipe diameters 160 mm coming out to distribute the air to the cushions. The latter have two valves from one side to allow the inflation of the two internal chambers of the cushion and a pressure relief valve to exhaust the chamber on the opposite side. The machine is connected with a weather station that will increase or decrease the internal pressure of the cushions ensuring the stability of the same in the case of wind or snow, increasing the pressure in the cushions: inner chamber of the cushion (pressure type A): from 330 Pa to 630 Pa; side chambers of the cushions (pressure type B): from 300 Pa to 600 Pa.

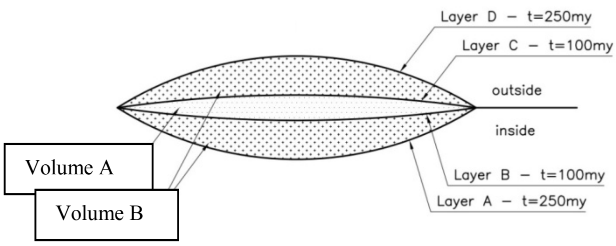

Figure 11: Volumes for different pressures into the air chambers of the etfe cushions (Source: Canobbio)

Figure 12: Pictures of the realization, from outside and inside (Source: Canobbio)

5. CONCLUSION

Through the design process, the engineering and the production of the building in object, it was possible to understand the experimental and empirical level related to the choice of the system dealing with energy issues, and choosing a technical solution that could meet the current architectural requirements for high performance coverings in terms of thermal and indoor comfort, answering to the need to reduce energy consumption of buildings and to satisfy the well-being in a closed environment. Definitely a significant and innovative approach from the design point of view, in comparison with the results achieved in the Winter Garden of Verona, could be the simulation of the solar path related to the covering and be of a great help to the strategic definition of the intensity and density of the printing on the ETFE cushions films in the areas mainly stressed by solar radiation. Also it would be necessary to have film or components matched to the ETFE which are able to transmit or reflect selectively the different wavelengths of the solar spectrum, in order to adapt to any application the overall performance of the covering. There are UV and IR filters whose range of treatments can affect the emissivity of the surface or the capability of the structure to radiate energy.

Assuming that the modeling of ETFE cushions, particularly in the case of curved shapes, added to the already curved shape of the cushions themselves, as part of the simulation of the energy performance of the building has not yet been explored, the performance of the system could be evaluated through computational fluid dynamics (CFD) testing or empirically the climatic chamber test (Hot Box), case by case. Besides understanding the optical properties of the transparent ETFE film and printed ones, by using a spectrophotometer[2], it would be desirable to investigate on one hand the optical properties of the films overlapped in parallel, both transparent and printed, maybe with a solar simulator and on the other hand the optical properties of the cushions with two / three films, transparent and / or screen printed, by using a special spectrophotometer, which enables to position the the film with an angle not perpendicular to the incident light flux, or even better with a solar simulator and define the optical parameters (transmission, reflection and emissivity) which allow the simulation of the real behavior of cushions in place. As a matter of fact, for example, the plane mock ups, made for the above mentioned project, have empirically been of great help, even though, the real effect of the printing and of the overlapping of the geometric patterns is again different and currently difficult to simulate.

Figure 13: Installation phase of the pneumatic evelope (Source: Canobbio)

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