SOFTENING THE HABITATS
SUSTAINABLE INNOVATION IN MINIMAL MASS STRUCTURES AND LIGHTWEIGHT ARCHITECTURES

Proceedings of the TensiNet Symposium 2019
Softening the habitats | 3-5 June 2019, Politecnico di Milano, Milan, Italy
Alessandra Zanelli, Carol Monticelli, Marijke Mollaert, Bernd Stimpfle (Eds.)

Assessment of building Physical Aspects of a New Angular Selective 3D – Prototype Foil (ETFE)

Jan CREMERS*, Hannes MARX*

*Stuttgart University of Applied Science, Schellingstr. 24, Stuttgart 70174, Germany,
jan.cremers@hft-stuttgart.de

Abstract

Buildings, which boast a high transparency into the façade or roof area without an appropriate sun protection, have a common problem of overheating due to solar heat gains (SHGC) in the summer. Especially lightweight-buildings with typical transparent materials, such as polymer-film of transparent ethylene-tetra-fluoro-ethylene (ETFE) have a very high solar transmission [T_{sol}] greater than 93% (200 μm).

The combination with a membrane cushion improves the thermal transmission coefficient (U-value) according to the number of layers (air gaps). A three-layer ETFE foil construction has an U-value of about 2.1 [W/m²K] (Knippers, 2011, p.216)].

For the unshaded case passive solar gains (SHGC) enter the building via the transparent ETFE foil cushion resulting in considerable high cooling energy loads and the risk of thermal- and visual discomfort (glare effects) in the summer case. In this paper we assess a new selective 3D-Prototype foil (sun protection) concerning the building physical aspect of the angle-dependent transmittance [τ], reflectance [ρ] and solar heat gain coefficients (SHGC) for the building envelope. Further aspects of this new development have been published before, cp. (Cremers and Marx, 2017a, 2017b, 2017c).

Keywords: ETFE, Solar energy, membrane cushion, prototype

DOI: 10.30448/ts2019.3245.01

Peer-review under responsibility of the TensiNet Association

1. Introduction

In this study, special modifications of plastic foils are investigated and developed in order to achieve a targeted regulation of the visual and solar radiation for the building envelope. A single layer of transparent ETFE foil (Nowoflon ET 6235 Z) has a solar heat gain coefficient (SHGC) of about 93 % (Product Data Sheet, Nowoflon) and the combination of a three layer foil construction with 2 air gaps of each 0.50 m has a SHGC of about 75 % (Nowoflon brochure, pp. 7). A well-established form to appropriately modify the visual and radiation properties is printing, tinting, coloring or applying coatings on foils. Compared to the current state-of-the-art shading technology, the main disadvantage of shading solutions for foils is the constant transmittance [T_{sol}] and reflection coefficient [ρ_{sol}] regardless of the incidence angle of the sun.

Therefore, the new 3D foil is based on the shed roof principle (saw-tooth roof) for sun protection.

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. The idea reflects on a realized ETFE building example, the shopping mall "Dolce Vita Tejo" close to Lisbon (Amadora), which possesses a shed roof principle of membrane cushion. The dimension of each membrane cushion is approximately 10 m x 10 m (Knippers, 2011, p. 256).

In this context we manufactured the selective prototype foil with a hemisphere geometry (diameter of 0.02 m) on a millimeter scale similar to a bubble wrap foil. As the first step in the manufacturing process, the foil is printed with a flat printing pattern adjusted to the sun position (Stuttgart, Germany) and the spatially transformed geometry (hemisphere), sub sequentially foil is spatially transformed.

This allows for the same geometry (hemisphere) to be simply adjusted by varying the printing pattern for each project regarding the location.

2. Pneumatic multilayer foil construction

2.1. Construction (ETFE foil cushion including the new 3D - Foil)

Basically, pneumatically stabilized multilayer foil constructions are clamped typically with an aluminum frame system at the edge, which is held by a corresponding load-bearing substructure (one layer ETFE foil ≈ 350 g/m² @ 200 µm). The pneumatically stabilized foil cushions can consist from two to five layers of foil. Conventional foil width for ETFE (Nowofol ET 6235 Z) is 1550 mm, whereby the foil length is optional. In order to guarantee greater wingspan, welding or gluing of the material (3D foil) is necessary for the future use. Conceivable joining techniques could be done by welds or UV-stable bonded joints. Characteristic foil thickness varies according to static and design requirements between 80 µm to 300 µm

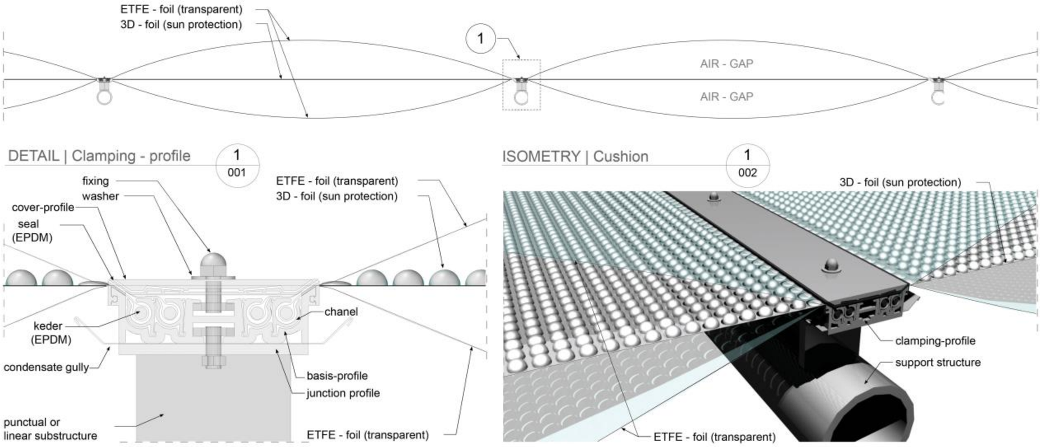

Figure 1: Pneumatic three layer foil construction: (ETFE transparent 200µm + 3D foil 250 µm + ETFE transparent 200µm)

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 with an U-Value of about 2.1 [W/m²K]. The shape of the cushion geometry for pneumatic multilayer foils is stabilized by a low-pressure air system at an overpressure level of approx. 200 Pa to max. 800 Pa, depending on the cushion size. Consequently, the benefit is: no external environmental influences of weathering, soiling, chemical influences (ambient air quality), contamination and cleaning processes. Furthermore, the exposition to UV radiation on the 3D foil can be additionally reduced by the external foil layer. Stress due to pressure- and suction effects e.g. by snow, water or wind loads can be targeted by cutting a small hole into the 3D foil to enable pressure equalization. This means that practically no mechanical stress is transmitted to the middle foil layer (3D foil). The power is transferred to the following inner foil layer.

This "protected installation" improves the durability of the 3D foil. Further benefits are no complex cutting patterns of the 3D foil, which means a significant cost reduction and manufacturing process within the planning.The new selective 3D – Prototype foil

3. The new selective 3D – Prototype foil

3.1. Material and coating

ETFE has a non-polar surface so therefore is a special procedure necessary in which increases the surface energy, this allows coating on ETFE foils (Moritz, 2007). However, the complex coating process and the random-like 3D-shape quality (no precise form) of ETFE foils (Nowoflon ET 6235 J @ 100 µm and 200 µm) after spatially transforming by thermoforming cf. Figure 2, left, have led to the choice of another suitable material for the first stage of the prototype foil. The 3D - prototype foil is made of Polycarbonate material (PC) with a thickness of 1000 µm that allows to achieve the effect.

A suitable ETFE material thickness for the 3D foil in the construction sector would be 250 µm to 300 µm for the practical usage. It is because a material thickness less than 200 µm indicates due a durable deformation regarding in manufacturing, packaging, transport and installation by one-off external power. Tests have shown this by manufactured ETFE foils in thickness of 100 µm and 200 µm. A material thickness higher than 300 µm is not suitable for economic use (referred to investment) and the technical limitations of the roll-to-roll process is max. 500 µm.

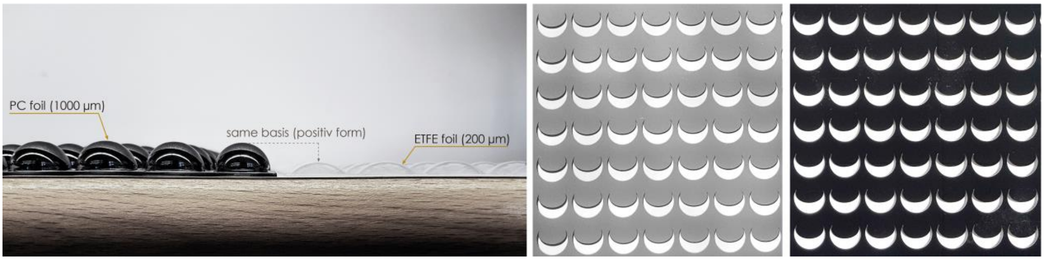

Figure 2: Prototype: spatially transforming of PC foil (1000 µm) and ETEF foil (200 µm); coating layers (silver and black).

A modified coating structure for the lighting- and radiance properties is determined by a repro- and screen printing process. The first layer is a black coating for minimum solar transmission (the view from inside). Afterwards, the second layer is a silver coating for maximum solar reflection coefficient (the view from outside).

3.2. Geometry and printing pattern

The geometry of the spatially transformed foil is a hemisphere and the additionally printing pattern considers the position of the sun by the zenith- and azimuth angles for Stuttgart, Germany. The hemisphere diameter is 20 mm (a) and the distance between each hemisphere is 3.21 mm (b), see Figure 3. The total printing proportion of the flat print (before spatial transformation) amounts to 76 % and the total printing proportion of the 3D foil changes due to spatial transformation to 63 %.

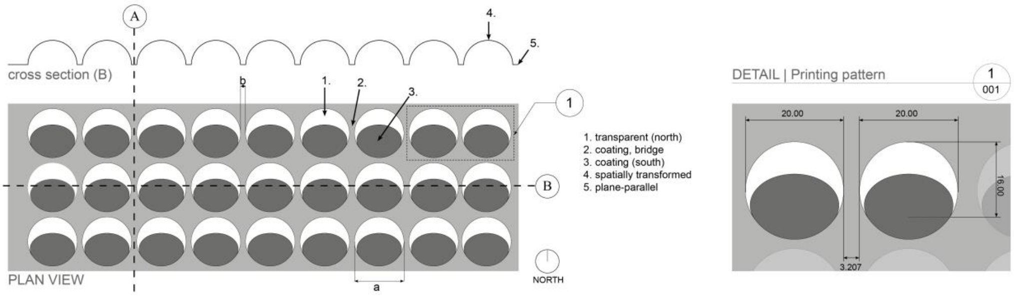

Figure 3: Plan view and Detail of the 3D Prototype

The coating on (2.) and (3.) have the same lighting- and radiance characteristics to minimise the solar transmission. Meanwhile, position (1.) should allow as much diffuse sunlight as possible to enter and does not require any additional coating (maximum visual transmission), see Figure 3.

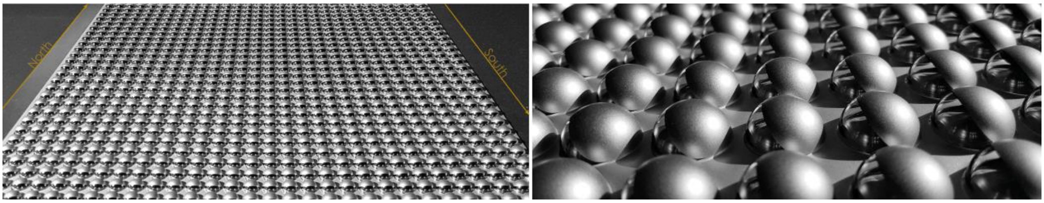

Figure 4: Finalized PC foil prototypes (dimension: 700 mm x 700 mm)

3. Building Physical Aspects

The important building physical aspects for a building envelop in summer is solar protection and in winter thermal insulation of the internal thermal condition (e.g. by thermal transfer, thermal radiation, thermal convection), sound insulation, sound absorption, control of humidity as well as the optical properties (e.g. SHGC, T, ρ, α). This is essentially for concept, planning, practical construction and utilization of a well-functioning building envelope.

Foil cushions have a highly dynamic thermal transmittance coefficient (U-value) which is significantly influenced by the thermal convection inside the cushion and radiation - and therefore by the membrane cushion geometry.

The multi-layer construction can reduce the thermal heat transfer but this leads to a change of the optical properties. Consequently, an assessment is made of the optical properties of the new angular selective sun protection (3D foil).

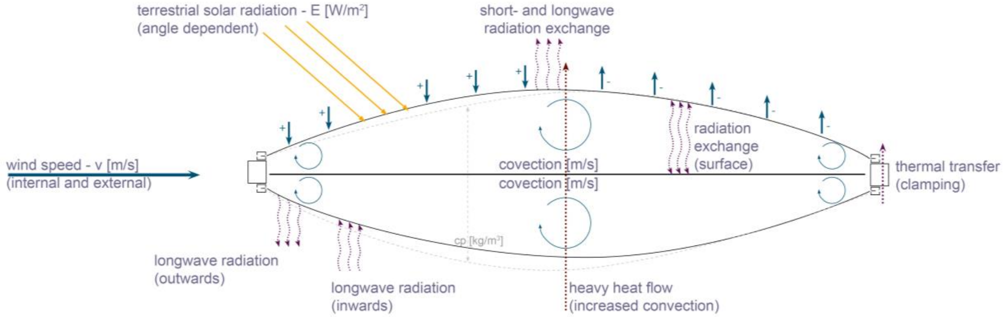

Figure 5: Building physical aspect of a multi layer foil cushion

4. Results and discussion

4.1. Optical Properties: Angular measurement data (spectral transmissions- and reflection coefficient)

For the manufactured selective prototype foil from paragraph 3, measurements of the angle-dependent variation of transmission- and reflection coefficient, in an interval of 15° to the surface normal were conducted. The vertical radiation source is at an angle of 90°. Meanwhile at an angle of 150 °, the radiation source is directed towards the transparent open north side of the hemisphere. At an angle of 30 °, the radiation falls on the fully printed south side.

Within the measurement, the simulation of the sun's solar path over the azimuth and zenith angles is not taken into account. There are two different variations in Figure 6, the black characteristic curve is a conventional flat printed ETFE foil with 65 % of silver printing "ETFE silver printing" and the new 3D foil with 63 % of silver printing: "hemisphere, printed".

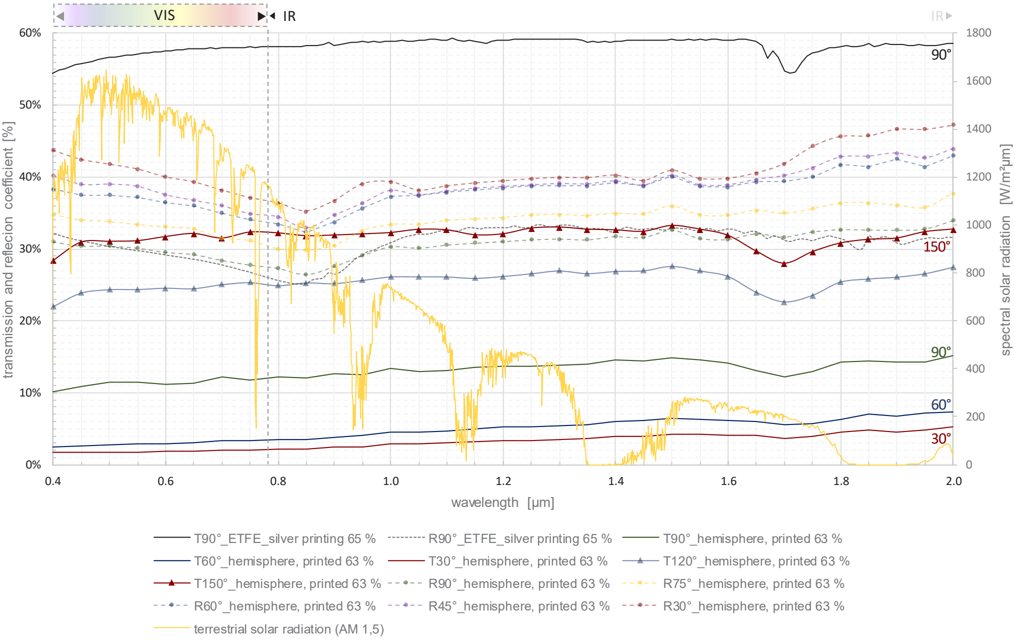

Figure 6: Spectral data (reflection- and transmission coefficient)

Figure 6 displays reflection and transmission coefficients for different angles in the wavelength range [λ] from 400 nm to 2000 nm. The spectrum of terrestrial solar radiation (AM 1,5) [W/m²µm] is plotted on the secondary axis. This is the primarily reason for the solar energy inside the building and for overheating.

A decrease of the transmission with the angles between 90° to 30° is recognizeable, meanwhile an increase of the transmission within the angles of 120° and 150° compared to the variant "ETFE silver printing" can be seen. As a result, the solar and visual transmittance within the 3D foil varies heavily depending on the angle of radiation. The absolute difference is around 30 % (T_{vis}-T_{sol}: 30-31 % at 150° and T_{vis} - T_{sol}: 2 % at 30°). Furthermore, the measurement indicates for the incident angle of 60°, the result of the spatial transformation can achieve an improvement by reducing the solar transmission by 87 % and the visual transmission by 82% compared to the variant without the spatially transformed (flat printing) on the basis of measurements.

Compared with the reflection coefficient of "ETFE silver printing 65 %", the 3D foil shows good agreement for the radiation incidence of 90°. The incidence of 30° shows an increase of the solar reflectance by a factor of 1.6 from 2D to 3D foil. The missing optical parameters (angles) were interpolated between the measured radiance properties done according to formula (1).

$$Y_n = Y_1 + \frac{Y_2 - Y_1}{x_2 - x_1} * (x_n - x_1) \tag{1}$$

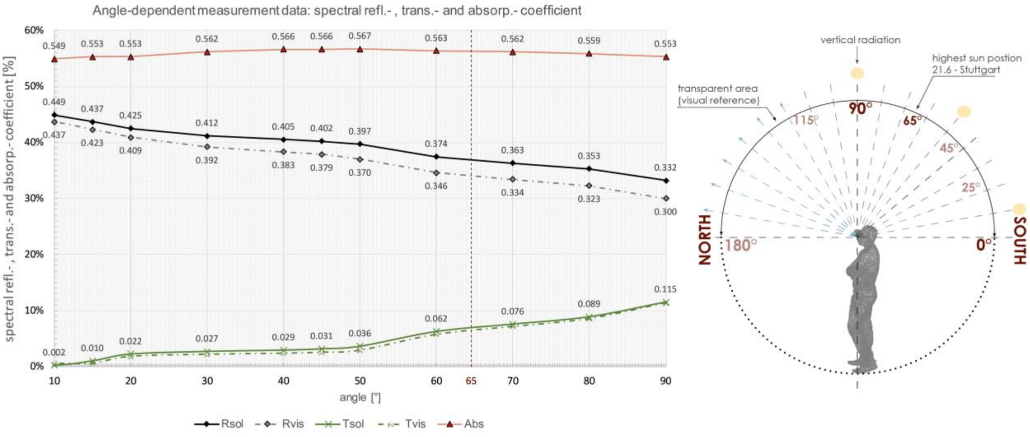

Figure 7: Angle-dependent reflection-, transmission- and absorption coefficient of new 3D foil material (Data interpolated from meassurements by ZAE-Bayern e.V.)

4.1. Solar Heat Gain Coefficient (SHGC)

The "SHGC" of the new angle selective 3D foil was measured at an outside sun test facility at ZAE-Bayern in the climate region of Würzburg "WU" (49.786°, 9.967°) (Germany). The sun position is very close to Stuttgart "STR" (48.776°, 9.183°) (Germany). The highest sun position in Würzburg is on June 21th with an angle of 64° (STR 65°), the lowest sun level is on December 21th with an angle of 17° (STR 18°) and the equinox is on March 21th with a maximum of 41° (STR 42°).

There are two different measurements of the angle to the sun (90° and 55°) for two variants of foils (2D and 3D). One version is the 3D foil as described in chapter 3 with the spatial transformation. The other version is the 2D foil, before the spatial transformation but with the identical printing pattern as the 3D foil.

Table 1: Solar heat gain coefficient (outside sun stand) in Würzburg, Germany. Measurement data by ZAE – Bayern.

Description	**Angle to the sun**	**Solar Heat Gain Coefficient (SHGC)**	**Deviation**
3D foil, hemisphere, printed 63 %	90°	0,26	+- 0,05
3D foil, hemisphere, printed 63 %	**55°**	**0,16**	**+- 0,05**
2D foil, plane, printed 76 %	90°	0,29	+- 0,05

2D foil, Plane, printed 76 %	55°	0,28	+- 0,05

The results of the "SHGC" measurement of change by spatially transforming at the angle of sun with 55° amount a reduction of 75 % (3D foil: 0,16 and 2D foil: 0,28).

5. Conclusion & outlook

This paper makes an assessment of building physical aspects, in detail of the optical properties (SHGC, T, ρ, α) of a new 3D – foil Prototype, by evaluation of measurements. The basis is the manufactured angular selective 3D – Prototype Foil for the location Stuttgart (Germany). One important special modification of the plastic foil was necessary. The foil is not only printed with a pattern, but also additionally spatially transformed through a hemisphere geometry. The modifications were made under the premise of sufficient daylight quality. Light is entering only by diffuse daylight through the transparent area of the hemisphere, in the style of the shed roof effect.

The significant aim of reducing the solar transmission (sun protection) of about the factor 2 compared to the flat printing (not additionally spatially transformed) is achieved for the relevant angles between 0° and 65° for Stuttgart.

The maximum solar transmission (T_{sol}) is 11 % at an angle of 90° to the sun. Meanwhile, at an angle of 60° to the sun transmission (T_{sol}) amounts to only 6 %. The solar reflection amounts to 37 % at an angle of 60° to the sun with a constant absorption coefficient of about 56 %. The "SHGC" amounts to 16 % at an angle of 55° to the sun.

The visual transmission (T_{vis}) amounts to 24 % at 120° and 31 % at 150°.

Table 2 lists a summary and comparison of all relevant optical properties. The angle dependent low level of "SHGC" by the 3D foil compared to the other solutions is very noticeable.

Table 2: Summary and comparison of the optical properties (ETFE, PC, Glass). Source: [1]: (Knippers 2011 p. 115), [2]: (Nowoflon brochure), [3]: (Schnittich 2006 p. 126), [4]: (Glastroesch).

	ETFE FOIL			PC FOIL			GLASS		
	SINGLE - LAYER[1] (transparent)	THREE - LAYER[2] (transparent)	THREE - LAYER[2] (IR-cut)	**2D - SINGLE - LAYER** (90°)	**3D - SINGLE - LAYER** (90°)	(55°)	SINGLE[3]	DOUBLE[4]	DOUBLE[4] (solar glass)
Thickness | Composition [µm]	F-200 µm	F-200 µm F-200 µm F-200 µm	F-200 µm F(IR)-200 µm F-200 µm	**F-1000 µm**	**F-1000 µm**	**F-1000 µm**	G-4 mm	G-6 mm A-16 mm G-4 mm	G-6 mm A-16 mm G-4 mm
Visible light transmittance [%]	92 %	71 %	44 %	**22 %**	**12 %**	**3 %**	89 %	41 %	19 %
solar transmittance [%]	93 %	74 %	36 %	**20 %**	**11 %**	**4 %**	83 %	20 %	12 %
visible light reflection [%]	7 %	24 %	11 %	**45 %**	**29 %**	**36 %**	8 %	18 %	29 %
solar reflection [%]	6 %	22 %	11 %	**45 %**	**31%**	**38 %**	8 %	32 %	25 %
Solar heat gain coefficient [%]	93 %	75 %	41 %	**29 %**	**26 %**	**16 %**	85 %	22 %	17 %
thermal transmittance coefficient [W/m²K]	6.9	2.1	2.1	**6.5**	**6.5**	**6.5**	5.6	1.0	1.1
printing proportion [%]	0 %	0 %	tinted	**76 %**	**63 %**	**63 %**	0 %	0 %	tinted

The next step will be to manufacture prototypes with ETFE foil with a thickness of 250 µm to 300 µm. Furthermore, it is possible to improve the coating with regard to a better reflection coefficient and this should lead to an even lower absorption coefficient.

Acknowledgements

The project "FMESG" is funded by the German

Federal Ministry for Economic Affairs and Energy

(BMWI, project code 03ET1309F).

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

References

Cremers J., Marx H. (2017a), 3D-ETFE: Development and evaluation of a new printed and spatially transformed foil improving shading, light quality, thermal comfort and energy demand for membrane cushion structures, CISBAT 2017, In *Energy Procedia 122 115-120*.

Cremers J., Marx H. (2017b), Improved daylight comfort by a new 3D-Foil that allows to trade off solar gains and light Individually, STRUCTURAL MEMBRANES 2017.

Cremers J., Marx H (2017c), A new printed and spatial transformed ETFE foil provides shading and improves natural light and thermal comfort for membrane structures, PLEA 2017, Volume III, 3620 – 3627.

Glastroesch, Product Data Sheet - Sun protection glasses (Silverstar), 2014.

Knippers J., Cremers J., Gabler M., Lienhard J. (2011). *Construction manual for polymers + membranes: Materials and semi-finished products, form finding and construction*. Munich, Germany, Edition DETAIL.

Moritz K. (2007) *ETFE-Folie als Tragelement*, Dissertation, Munich, Germany, Technical University Munich

Nowoflon, Product Data Sheet, Physical Properties Nowoflon ET 6235 Z (2015).

Nowoflon, brochure, Nowoflon ET 6235 Z-IR, ETFE Heat Absorbing Film (2015).

Schnittich, Staib, Balkow, Schulter, Sobek (2006), *Glasbau Atlas* Munich, Germany, Edition DETAIL.