JANUARY 17TH 2019 – MUNICH

# POWERSKIN CONFERENCE

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The building skin has evolved enormously over the past decades. Energy performance and environmental quality of buildings are significantly determined by the building envelope. The façade has experienced a change in its role as an adaptive climate control system that leverages the synergies between form, material, mechanical and energy systems in an integrated design.

The PowerSkin Conference aims to address the role of building skins to accomplish a carbon neutral building stock. Topics such as building operation, embodied energy, energy generation and storage in context of envelope, energy and environment are considered. The 2019 issue of the conference PowerSkin focuses on the digital processes in façade design and construction, showcasing presentations about recent scientific research and developments in the field.

The **Technical University of Munich**, Prof. Dipl.-Ing. Thomas Auer, **TU Darmstadt**, Prof. Dr.-Ing. Jens Schneider and **TU Delft**, Prof. Dr.-Ing. Ulrich Knaack are hosting the PowerSkin Conference in collaboration with the trade fair **BAU 2019**, supported by the national funding initiative **Zukunft Bau (BBSR)**. It is the second event of a biennial series. On January 17th, 2019, architects, engineers, and scientists present their latest developments and research projects for public discussion.

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Ulrich Knaack, TU Delft
Jens Schneider, TU Darmstadt

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Véro Crickx, Sirene Ontwerpers
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# 4dTEX – Exploration of Movement Mechanisms for 3D-Textiles Used as Solar Shading Devices

**Claudia Lueling[1], Johanna Beuscher[2]**

1 FFin Frankfurter Forschungsinstitut, Frankfurt University of Applied Sciences, Frankfurt am Main, Germany, email: clue@fb1.fra-uas.de

2 FFin Frankfurter Forschungsinstitut, Frankfurt University of Applied Sciences, Frankfurt am Main, Germany

**Abstract**

*Three-dimensional, multi-layer textiles offer specific, constructive-aesthetic possibilities due to their individually adjustable material thickness. They also offer spatially effective modification options via special, still unexplored movement options with low energy input. Movement and the time factor are thus integrated into the textile design as a fourth dimension. Fibre-based high-tech materials have long been used in solid and lightweight construction for reinforcement, solar protection and insulation. In this context, the Textile Lightweight Construction Division of the Frankfurt Research Institute FFin is researching dynamic construction components in combination with textile multilayer structures made of so-called spacer textiles. In the project described below, movement mechanisms for opening and closing or for the control of viewing and incident light from spacer textiles are presented with the aim of developing robust and low-maintenance components for facades. When closed, they can also temporarily reduce energy loss or the heating up of the rooms behind them. Based on traditional sun protection systems such as shutters, venetian blinds and pleated blinds, the FFin is investigating on the one hand the controllable daylight management of multi-layer textiles used as moveable elements as a whole on the macro level, and movements in the textile structure itself, that is to say in the meso level of the spacer textiles on the other.*

**Keywords**

*Solar shading, spacer fabric, 3d textiles, dynamic movements, digital textile*

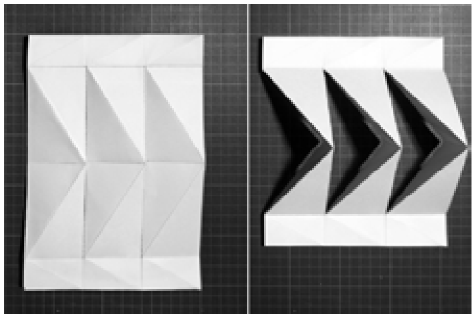


FIG. 1 Origami/kirigami, paper experiment

FIG. 2 Textile folds, Semira Boon

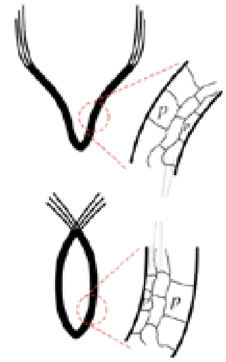


FIG. 3 "Venus trap" principle

# 1 INTRODUCTION

Over the millennia and often without architects and engineers, solutions have been developed for a wide variety of climate zones for the facade as mankind's active, third skin, both in solid and lightweight construction. They help adjust the comfort level in buildings as required. Building and construction history thus offers sophisticated low-tech solutions that by themselves, however, are no longer sufficient for today's energy and above all electricity requirements. For the future, an intelligent combination of low-tech and high-tech is needed that continues to actively integrate the user in parts and which takes into account local circumstances.

Research is focusing in particular on lightweight and textile construction. Traditional examples such as yurts show the potential of adaptive textile-based lightweight construction solutions for self-supporting wall and roof systems, yurts being perfectly prefabricated, transportable structures with three centimeters of felt skin in summer and an adaptive triple, nine centimeters-thick felt cover against temperatures as low as minus 40°C in winter. This category also includes textile, external solar protection systems as quasi archaic systems in the opening area. Following on from this, technical textiles such as 3D and spacer textiles made from highly-developed fibre materials and manufactured on high-tech machines offer the opportunity to advance the evolution of the building envelope with modern means.

The investigation described below focuses on the most sensitive area of the outer skin of the building – the opening area. The object of the investigation is the extent to which multilayer textiles such as spacer textiles can be used as moveable, possibly adaptive solar protection and at the same time as temporary heat protection. The work is based on the research project "ReFaTex – reversibly foldable, energetically-effective 3D textiles in the building sector" (funding line – Innovationsfonds Forschung). This involves the production of ultra-light and stable elements from spacer textiles in the facade area, which should also be foldable and, depending on requirements, opaque and translucent to transparent. In the course of the research, the term "foldable" was replaced by "moveable" in order to comprehensively capture the dynamic potential of spacer textiles.

FIG. 4 Spacer textile, © Culzean

## 2 METHODOLOGY

An empirical and experimental methodology was chosen for the research project. At the beginning, experimental investigations with spacer textiles on a 1:1 basis are carried out and optimised by the research team in an iterative process, involving student seminar papers. At the same time, intensive research is carried out on folding technologies, including origami and in combination with kirigami, a paper-cutting art (Fig. 1). In addition, findings from previous research on textile folds on an architectural scale are incorporated (Fig. 2) and inspirations from nature (Fig. 3) included, with soft material transitions, bends, hingeless joints as well as complex unfolding patterns in animals and plants being considered.

Finally, the discovered movement mechanisms are systematised and evaluated in tabular form. Based on traditional solar protection typologies such as shutters, venetian blinds and pleated blinds, the aim is to identify movement possibilities on both the macro and meso levels which, due to the use of specially-made spacer textiles, offer new options for light control and visual references in the solar protection area, while at the same time making use of the natural insulating properties of spacer textiles.

Within the framework of the project, the term macro level is used to refer to the movement of the entire textile solar protection element in front of the facade opening. The textile structure itself is defined as the meso level, with the textile geometry in particular being examined. The aim is to identify further specific movement options within the textile structure without moving the entire element, in order to achieve possibilities for changes in translucency in the surface up to opacity.

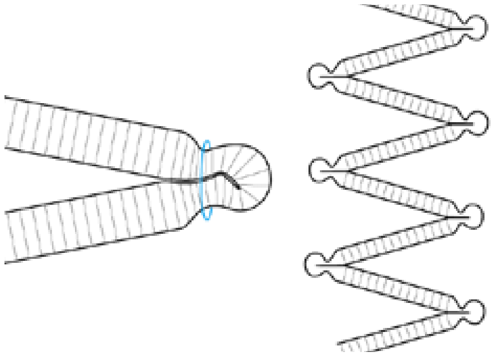


FIG. 5 Directional folding structure by stitching

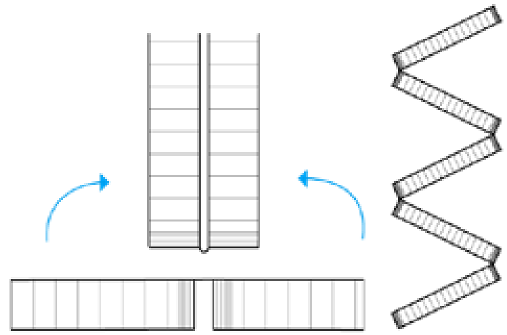


FIG. 6 Directional folding structure by incision

FIG. 7 Solar shading element, made of folded spacer textile

# 3 EXPERIMENTS

## 3.1 FOLDING AND CUTTING

Multi-layer spacer fabrics can already be produced on a laboratory scale and industrially in such a way, that they have different thicknesses due to the varying spacing of the textile layers. Stiff or thick and moveable or thin areas can be arranged alternately accordingly (Fig. 4). In this way undirected folding areas are created, which function equally as mountain and valley folds but which are correspondingly unstable in use. The textiles can thus be folded together collectively (macro level), while a defined basic transparency can additionally be set on the meso level via textile cover layers of varying density. Directional, more stable folding structures, comparable to pleated blinds, can alternatively be achieved by subsequent finishing (Fig. 5) or by alternating partial incisions in the spacer textile while maintaining the top layer opposite the incision (Fig. 6).

Fig. 7 shows a corresponding demonstrator on a 1:1 scale. Hingeless joints are achieved with the partial incisions, and transparent areas for inward and outward views are also generated with continuous incisions in the textile structure. New pleated structures are created, which can also be used as external solar protection (protected system). To this end, the stability of the textile is increased by coating or partial fillings. Robust elements can be achieved in particular by foaming in the area of the edges (see research on "3dTEX – Textile light wall element"). Further applications are currently being developed for window shutters, lift-up shutters and folding shutters as well as pleated blinds in other geometries.

## 3.2 BENDING, COMPRESSING AND STRETCHING

Naturally, fabrics are subject to "soft wrinkling", and therefore the subject of bending and bending mechanisms is another focus of the investigations. The elements realised so far appear accordingly to be much more "material"-like and softer than the folding structures. On the meso level, bending of the spacer textiles results in the texture of the inner surface layer being automatically compressed or condensed. The bending movement can so be used to selectively adjust areas with lower translucency (Fig. 8). Consequently, on the macro level, this means that the entire element must be correspondingly larger than the opening element. At the same time, the elements made of spacer textiles can be moved completely out of the opening area by increased bending and additional compression. As a whole, they resemble a thick, translucent curtain. Through targeted vertical stabilisation within the surface layers, the elements can also be mounted externally, comparable to the above-mentioned folding systems.

FIG. 8 Spacer textile, bending by shirring

FIG. 9 Spacer textile with partially elastic regions

FIG. 10 Spacer textile, offset cut and stretched

FIG. 11 Spacer textile, selectively stretched

FIG. 12 Spacer textile, cover surfaces stretchable in opposite directions

Moreover, warp-knitted spacer fabrics due to their mesh structure as well as woven spacer fabrics with elastic fibre components can be stretched. Like when the textiles are bent, the stretching movement changes the translucency. This can be influenced by tensioning on the entire textile structure in the surface axis, whereby the textile structure stretches and becomes more translucent (Fig. 9). Alternatively, it is possible to prepare the spacer textile by making offset incisions in the cover surfaces, so that stretching and transparency result from the pulling. The cover surfaces are then only held together by pile threads (Fig. 10). The elongation of individual, pile-thread-free textile areas perpendicular to the cover surfaces was also investigated (Fig. 11) and the elongation of individual, linear, opposite cover surface zones by bulging. Here, gill-like opening zones with an organic appearance are created that allow outward views (Fig. 12). All the mechanisms are protected.

## 3.3 MOVING AND FILLING

Stretchability or elasticity, compression or squeezing, just like folding, bending and rolling, are classic ways of transforming spacer textiles. The programmable geometry of the special textiles is decisive for the functionality of all these mechanisms:

The top layers of woven and knitted spacer textiles are kept at a distance from each other by so-called pile yarns. The number and position of the pile yarns as well as the density of the surfaces and the pile yarns can be defined. If only the meso level of this textile structure is considered, the most obvious and simplest movement option is the displacement of cover layers of different densities to each other (Fig. 13). This counter-rotating movement in the x- or y-axis of the textile allows light incidence and transparency to be controlled. This concept, too, is protected and will be further developed industrially. As a further option, the filling of the textile structure with magnetic colour particles is being investigated (Fig. 14). By incorporating electrically activatable magnetic metal fibres in the opposite cover layers, the position of the colour particles can be controlled, i.e. either the side facing towards or away from the building. The aim is to achieve a targeted reflection or absorption of sunlight depending on the season. At the same time, the research project is investigating filler material for densifying the three-dimensional textile structure with the aim of adaptively controlling shading and viewing at specific points and depending on sunlight incidence (Fig. 15).

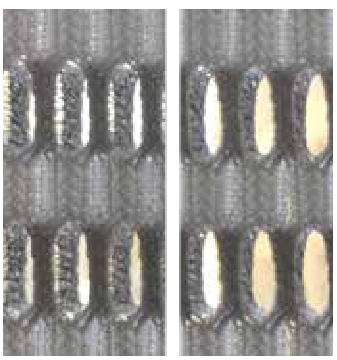


FIG. 13 Displacement of the cover surfaces of a spacer textile with respect to each other


FIG. 14 Spacer textile with side-based magnetically activatable colour particles


FIG. 15 Spacer textile filled with adaptive foam particles

# 4 RESULTS

Classical textiles are non-rigid, flexible semi-finished products whose basic moveability permits surface-related movements and size changes by, for example, controlled folding or unfolding, bending, shirring, crimping or stretching. At the same time their stability can be increased e.g. by folding or impregnating. These possibilities can be further enhanced by the use of three-dimensional textiles. Both the special movement options and the individual stiffening options of three-dimensional textiles allow the development of geometrically complex and high-quality design, stable, lightweight, translucent and opaque components as well as transparent components in certain areas. They offer passive solar energy gains in the opening area of buildings, such as protection against overheating and increased overall user comfort. In the 4dTEX project, the experimentally achieved results were processed and compared in tabular form in order to enable the comparison and evaluation of the results obtained with regard to the geometry of the textiles.

## 4.1 FLAT SOLAR PROTECTION ELEMENTS/ SHUTTERS

Fig. 16 show flat solar protection elements based on classic shutters such as folding, sliding, window, lifting and roller shutters. In lines 1 and 2, category A, these mechanisms are first categorised on the macro level. In columns 5, in particular, initial mechanisms can be recognised which can only be realised with textiles, and in particular with stretchable textiles. Category B, line 2, shows on the meso level the possibilities that exist beyond this and through use of the special geometry of three-dimensional textiles. This is where the experimentally achieved results come in. In addition, further options or possible variations of these results appear, as shown in particular in columns 2, 4 and 5. Categories C and D show additional findings on how the thermal properties of spacer textiles can be improved and how other active and passive uses of solar energy can function. Results such as foaming with flexible foams or alternatively the use of strongly crimped fibres for insulation are currently being used for the preparation of further research projects, as are the use of light-conducting fibres and the question concerning the use of volume-adaptive foams. Findings are also being used for the development of unfoamed spacer textiles with elastic pile yarns (also called FGL yarns) for controlling the element thickness (column 4) as well as for unfoamed spacer textiles with electromagnetically-controlled PCM-based colour pigments (column 5). Category E additionally shows potential filter functions (pollen filter, fog filter/water trap) as well as the sound-absorbing possibilities of the textile elements.

Finally, one of the experimentally and tabularly elaborated options of a flat element was examined in terms of its design. A pneumatically or adaptively controlled stretching mechanism perpendicular to the textile surface was selected. It is used for the selective control of incident daylight and the simultaneous increase of transparency in areas that are not shaded. Fig. 17 shows a corresponding facade simulation.

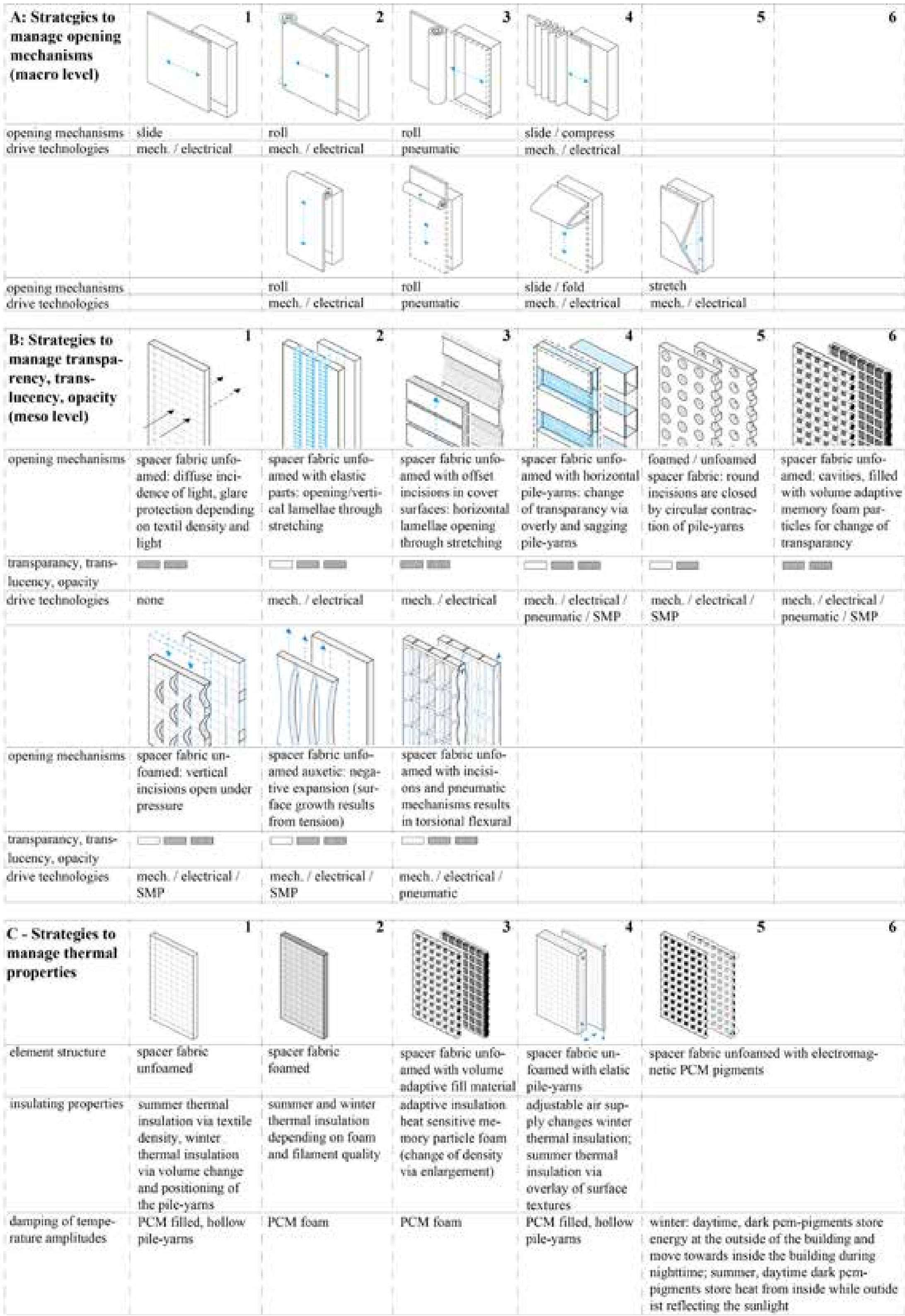
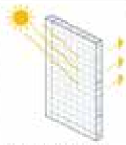
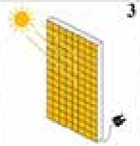
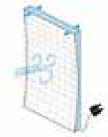



FIG. 16 .1 Shutters: A, B, C

| D - Strategies to manage passive and active use of solar energy | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| |  |  |  |  | | |
| mechanism | light-conducting fibers | spacer fabric used as solar collector | textile solar cells | piezoelectric | | |
| light guidance | daylight management via light-conducting fibers | | | | | |
| power or heat generation | | heat generation along the fur structure of icebears | power generation along the research on semiconductor and coating technologies | power generation via micro movenments initiated by wind suction / pressure | | |

| E - Others: Strategies to manage air filtration, sound insulation, water extraction | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| |  |  |  | | | |
| mechanism | spacer fabric unfoamed, open pored | spacer fabric unfoamed, open pored | spacer fabric unfoamed, open pored | | | |
| functionality | filter for fine dust, pollen, insects | sound insulation depending on density, weave or knitting structure | textile fog collector | | | |

transparent
transluzent
opak
SMP Shape Memory Polymer

FIG. 16 .2 Shutters: D, E

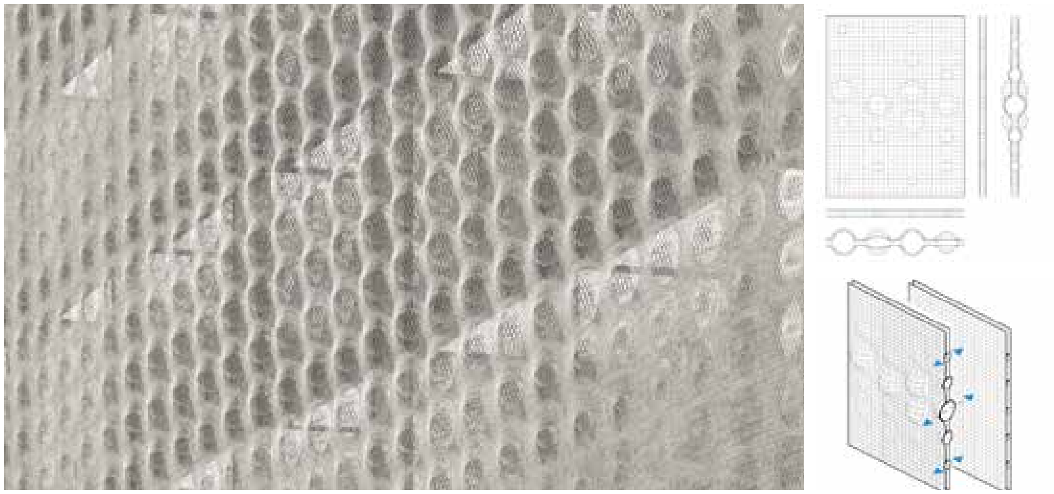
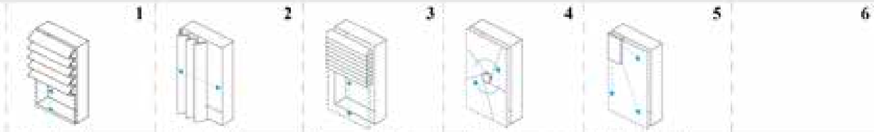


FIG. 17 Spacer textile, selectively stretched and in line with sunlight

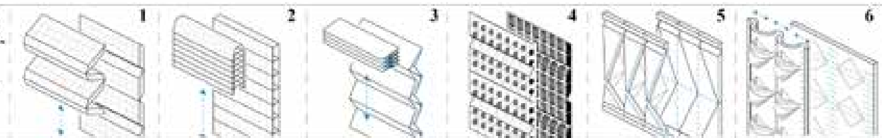
FIG. 18 Folded and cut spacer textile for exterior sun protection

## 4.2 FOLDED, CURVED SOLAR PROTECTION ELEMENTS (PLEATED BLINDS)

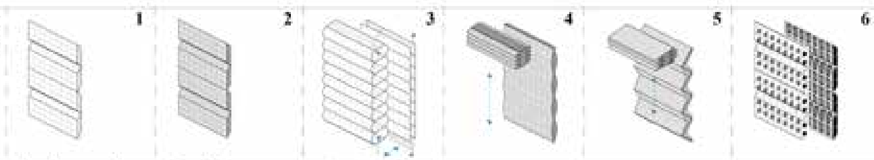
Fig. 19 shows in lines 1 and 2 of category A (macro level) folded solar protection elements, i.e. pleated blinds including honeycomb pleated blinds. Here again, in columns 4 and 5 (Miura folding) in particular, initial mechanisms can be recognised, which can be realised above all with 3d textiles and in particular partially  elastic textiles. Category B, line 2 shows on the meso level which other possibilities arise through the use of the special geometry of three-dimensional textiles. This is where the experimentally achieved results come in. In addition, further options or possible variations of these results appear, as can be seen in columns 2 and 6 in particular. The latter shows the development of a thermally optimised, three-layer pleated or honeycomb pleated blind.



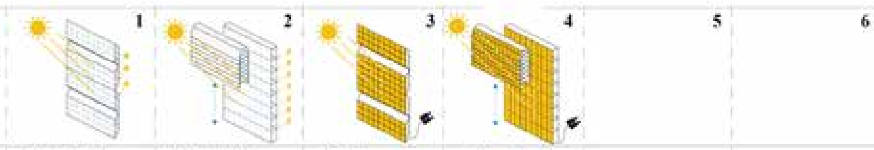
| A: Strategies to manage opening mechanisms (macro level) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| opening mechanisms | pleated, pull | pleated, slide | honeycomb pleats, pull | radial pleats, rotate | double pleat, flap and fold | |
| drive technologies | mech. / electrical | mech. / electrical | mech. / electrical / pneumatic | mech. / electrical | mech. / electrical | |



| B: Strategies to manage transparency, translucency, opacity (meso level) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| opening mechanisms | pleated spacer fabric unfoamed: diffuse incidence of light, glare protection depending on textil density and light | honeycomb pleat made from spacer fabric: diffuse incidence of light, glare protection depending on textil density and light | honeycomb pleat (3-layer spacer fabric unfoamed): diffuse incidence of light, glare protection depending on textil density and light | pleated spacer fabric, unfoamed, filled with heat sensitive memory particle foam (change of transparency via enlargement) | spacer fabric unfoamed or foamed, with pleats and vertical incisions, offers transparency, translucency and opacity | spacer fabric unfoamed or foamed, with pleats and vertical incisions, offers punctual transparency via bending |
| transparancy, translucency, opacity | | | | | | |
| drive technologies | mech. / electrical | mech. / electrical | mech. / electrical | mech. / electrical / pneumatic / SMP | mech. / electrical | mech. / electrical / SMP |



| C - Strategies to manage thermal properties | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| element structure | pleated spacer fabric or honeycomb pleat, unfoamed | pleated or honeycomb pleat spacer fabric, foamed | unfoamed honeycomb pleat spacer fabric, with pneumatic or SMP based volume change | honeycomb pleat spacer fabric filled with elatic foam | honeycomb pleat 3- layer spacer fabric: inner layer foam or made from 3d-crimped fibers | pleated spacer fabric or honeycomb pleat, filled with volume adaptive foam |
| insulating properties | summer thermal insulation via textile density, winter thermal insulation via volume change and/or positioning of the pile-yarns | summer and winter thermal insulation depending on foam and filament quality | summer thermal insulation via textile density, winter thermal insulation via volume/distance between the cover layers | summer and winter thermal insulation depending on foam and filament quality | summer and winter thermal insulation depending on foam and quality of 3d-crimped fibers | fill material: heat sensitive, memory form particel foam adapts volume (density) |
| damping of temperature amplitudes | PCM filled, hollow pile-yarns | PCM foam | PCM filled, hollow pile-yarns | PCM foam | PCM filled, hollow pile-yarns | via change of the elements desity |



| D - Strategies to manage passive and active use of solar energy | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| mechanism | light-conducting fibers | light-conducting fibers | textile solar cells | textile solar cells | | |
| light guidance | daylight management via light-conducting fibers | daylight management via light-conducting fibers | | | | |
| power or heat generation | | | power generation along the research on semiconductor and coating technologies | power generation along the research on semiconductor and coating technologies | | |

FIG. 19 Folded Blinds

FIG. 20 Bend and compressed spacer textile for external solar protection

Categories C and D show, as already with the flat elements, additional results. Thermal properties and other active and passive uses of solar energy can also be implemented in the folded textile elements due to the three-dimensionality of the textiles. In particular, columns 4 and 5 of category C, which represent geometric variations of honeycomb pleated blinds manufactured as spacer textiles, show how the thermal properties have been further developed as regards insulation. Category E shows the same options as already described for the shutters.

Finally, one of the experimentally and tabularly elaborated options of a folded element was examined in terms of its design. A folded and cut surface with comparable functions to the flat element in Fig. 17 was selected: Selective control of incident daylight with simultaneous increase of the transparency in areas that are not shaded. Fig. 18 shows a corresponding facade simulation.

## 4.3 MIXED TYPOLOGIES

In the 4dTEX project, venetian blinds were also investigated as a third typology. Here there were no geometrically-induced new solar protection elements made of spacer textiles. The main result was that three-dimensional textile production could enable the manufacture of venetian blinds in a single industrial step. Whether this makes commercial sense was not further evaluated.

For 4dTEX, exciting results have emerged in the field of mixed typologies. Should bending (Fig. 20) already be a special case of folding, the elements shown in Fig. 9 can be described as "Stretch_Bend_Venetian_Roller". And the element depicted in Fig. 21 also represents a typological special solution. Based on the torsional flexural buckling mechanism realised at the University of Stuttgart under the name "FlectoFold", a torsional flexural fold is triggered by bending the spacer textile. The bending has already been investigated in advance with respect to design and in the form of a facade simulation (Fig. 8). In combination with the FlectoFold mechanism, this could for the first time not be generated additively in individual elements but from a surface which, in addition to the bending, also allows areas with partial openings for viewing.

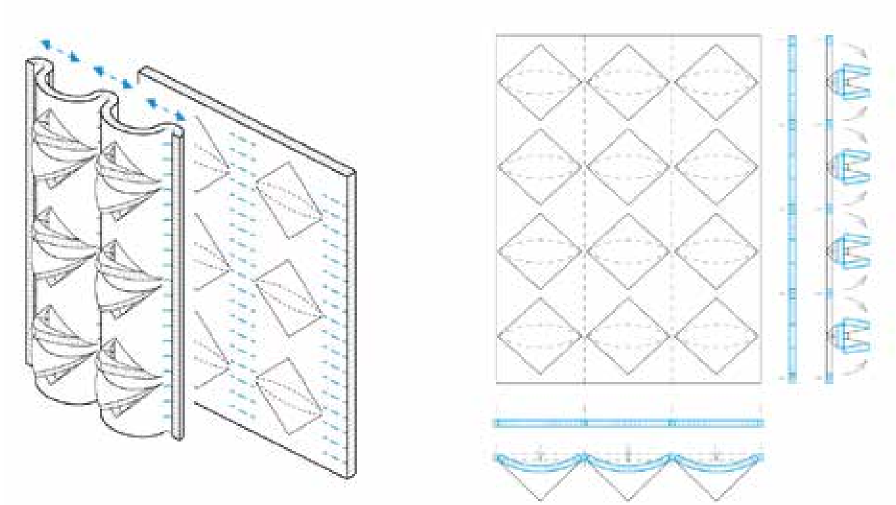


FIG. 21 Torsional flexural buckling in the surface

## 5 CONCLUSIONS

In summary, the theory can be confirmed that, with the help of three-dimensional textile technologies, new design and functional options for moveable, solar shading and insulation elements can be created. The results make the enormous potential of spacer textiles in the solar protection area – especially on the meso level (all the systems are now protected) – abundantly clear. The research project also shows that the conception of these complex three-dimensional structures can be effectively represented in the first step using drawings and sketches as well as with adapted, marketable spacer textiles. At the same time, the production of textile samples is very time-consuming, and therefore the next project proposal will include the question of how on the one hand the digital simulation of these textile structures can be improved, and how on the other the interface of this simulation software to the software used on the textile machines can be designed in the future. The aim is to better synchronise architectural and structural concerns with the manufacturing techniques and possibilities of textile production.

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### References

Anand,S., Soin,N., Shah, TH. & Siores, S. (2016) Energy harvesting "3-D knitted spacer" based piezoelectric textiles. Published under licence by IOP Publishing Ltd IOP Conference Series: Materials Science and Engineering, Volume 141, Number 1 doi:10.1088/1757-899X/141/1/012001899X/141/1/012001

Baesch, B., Friedrich, M., Riethmüller, C., Engelmann, J., Bauder, H.-J., Gresser, G. T. (2017) Lichtlenkende Multiaxialgewebe für das gezielte Management von Kunst- und Tageslicht. Quelle iTV Vortrag C. Riethmüller. For more information see https://www.ditf.de/files/inhalt/forschung/Kurzveroeffentlichungen/igf17818.pdf

Jackson, P. (2011). Von der Fläche zur Form - Falttechniken im Papierdesign. Berlin: Haupt Verlag

Knippers, J., Schmid, U. & Speck, T. (2017). Baubionik - Biologie beflügelt Architektur. Stuttgart: Naturkundemuseum Stuttgart

Knittel, C., Nichola, D., Street, R., Schauer, C. & Dion, G. (2015). Self-Folding Textiles through Manipulation of Knit Stitch Architecture. Fibers 2015, 3, Seite 575-587. For further information see doi:10.3390/fib3040575 www.mdpi.com/journal/fibers

Lüling, C.& Richter, I. (2017) Architecture Fully Fashioned - Exploration of foamed spacer fabrics for textile based building skins. Journal of Facade Design and Engineering, [S.l.], v. 5, n. 1, p. 77-92, jan. 2017. ISSN 2213-3038. For more information see https://journals.library.tudelft.nl/index.php/jfde/article/view/1526>. Date accessed: 29 Aug 2018. doi: https://doi.org/10.7480/jfde.2017.1.1526.

Morgan, J., Magleby, S. P. & Howell, L.L. (2016). An Approach to Designing Origami-Adapted Aerospace Mechanisms. Journal of Mech. Design 138(5) 2016/03 For more information see doi:10.1115/1.4032973 https://www.researchgate.net/publication/298334478_An_Approach_to_Designing_Origami-Adapted_Aerospace_Mechanisms

Nachtigall, W. & Pohl, G. (2013). Bau-Bionik, Springer-Verlag Berlin Heidelberg

Qiu, L., Deng, J., Lu, X., Yang, Z. & Peng, H. (2014). Integrating Perovskite Solar Cells into a Flexible Fiber. Angew. Chem., 126: 10593–10596. doi:10.1002/ange.201404973

Wang, Z. & Hu, H. (2014). Auxetic Materials and Their Potential Applications in Textiles. Textile Research Journal 2014/07. For further information see doi 10.1177/0040517512449051 https://www.researchgate.net/publication/263619275_Auxetic_Materials_and_Their_Potential_Applications_in_Textiles