PAOSS

Pneumatically Actuated Origami Sun Shading

Christina Eisenbarth[1], Walter Haase[1], Yves Klett[2], Lucio Blandini[1,3], Werner Sobek[1,3]

* Corresponding author
1 ILEK Institute for Lightweight Structures and Conceptual Design, Faculty 2: Civil and Environmental Engineering, University of Stuttgart, Germany, christina.eisenbarth@ilek.uni-stuttgart.de
2 IFB Institute of Aircraft Design, Faculty 6: Aerospace Engineering and Geodesy, University of Stuttgart, Germany
3 Werner Sobek AG, Stuttgart, Germany

Abstract

This paper describes the development of an innovative, material- and energy-efficient façade concept: a pneumatically actuated Origami sun shading system - abbreviated "PAOSS" - which combines the aesthetic and material-immanent qualities of textile materials with the functional aspects of a controlled and targeted light transmission regulation by means of integrated active pneumatic components (Fig. 1). Due to the possibility of reducing a given surface to a minimal form, textile-based folding structures are highly suitable for selective sun and glare protection systems, in order to optimise energy consumption and increase user comfort. For astrophysical purposes, the American space agency (NASA) developed an Origami folding geometry called "Starshade," which is characterised by a particularly high difference between its closed and open state. Inspired by NASA's "Starshade," an adaptive, pneumatically actuated sun and glare protection system was designed and developed to be embedded in the cavity of pneumatically supported multi-layer ETFE cushion façades. By implementing active components, one can obtain a targeted, partial, or full-surface regulation of light and radiation transmission as well as the back-reflection properties of the façade. Within the scope of the research project "Adaptive Membrane Façades" funded by the research initiative Zukunft Bau, the PAOSS will be prototypically built at a scale of 1:1 and implemented on one storey of the demonstration high-rise building of the Collaborative Research Centre 1244 entitled "Adaptive Skins and Structures for the Built Environment of Tomorrow." The goal is the system validation and the monitoring of its reliability and efficiency, especially in terms of building physics and daylight performance under real weather conditions.

Keywords

Adaptivity, textile, pneumatic cushion, sun shading, glare protection, origami folding, façade

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1 INTRODUCTION

Nowadays, several solutions are available to provide active sun and glare protection: the majority of these systems use mechanically or electronically operated actuation technologies, being highly sensitive to defects, material deterioration, system failures, and obsolescence. Moreover, they are characterised by a higher resource consumption in terms of the embodied material and the required operating energy. Thus, the challenge is to develop solutions, that combine high performance and low technological requirements with a minimum of energy and material use. (Meagher, 2014)

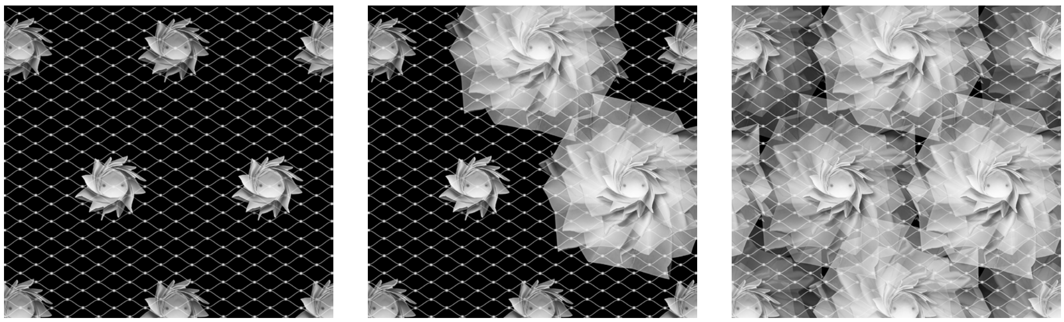


FIG. 1 PAOSS in closed state (left), in partially actuated state as selective glare protection (middle), and in open state as full sun protection (right). Copyright by ILEK / Visualisation by Christina Eisenbarth

The purpose of PAOSS is to combine an efficient kinetic sun and glare protection geometry with a lightweight textile high performance material by using a simple, resilient, and low energy actuation mechanism. The development takes place in an iterative process of design research and evaluation, that is briefly introduced in the following paragraph.

In a first step, the basic folding geometry of the system (NASA`s "Starshade" Origami folding) has been optimised in terms of efficiency and applicability as sun and glare protection in the façade cavity. In a second step, the spectral transmittance, absorption, and reflection properties of conventional textile sun protection materials were analysed and, based on the photo spectrometric measurements, the most suitable material was identified. In a further step, manufacturing methods for producing the folding geometry, that are applicable to different textile-based materials, have been investigated. Furthermore, concepts to integrate the pneumatic actuators as well as the synergistically optimised implementation of the PAOSS elements in an overpressure-stabilised ETFE façade system by using the existing air infrastructure have been examined. Future research will focus on the prototypical realisation of the PAOSS at a scale of 1:1 under real weather conditions in order to evaluate their functionality and durability.

1.1 SUN AND GLARE PROTECTION

Office and residential buildings are becoming more and more transparent, whereas current climatic developments require planners to move in the opposite direction, towards protecting our interiors from the rising global temperatures and from overheating caused by high solar radiation input. (Blandini, 2020; Blandini & Grasmug, 2018)

Particularly in dense urban areas, a significant temperature increase due to the urban heat island effect is noted. Therefore, it is important to provide an efficient sun and glare protection system with a low energy demand for activation. The large-area glass façades transmit incoming solar radiation and lead to a high cooling demand. This has to be compensated by oversized technical building equipment leading to higher heat stresses on the exterior environment. Suitable sun shading and glare protection systems are urgently needed in order to reduce the demand of energy required for interior conditioning and lighting, thus ensuring the users' need for sufficient daylight and visual contact to the outside. This has to be achieved with a minimum amount of material, mass, and CO_2 together with maximum aesthetic and design flexibility (Magli, Lodi, Lombroso, Muscio & Teggi, 2015).

In this context, it is essential to clearly distinguish the terms *sun protection* and *glare protection* from each other. The characteristic function of a sun protection is to shield high solar radiation from the building. A basic distinction is made according to the position of the sun protection system in the interior, the exterior, or in the façade cavity. While external systems are the most effective in terms of reducing solar transmission and heat transfer, they are also vulnerable to weather influences such as wind loads. On the other hand, interior systems are protected from climate influences, whereas the passage of solar radiation through the façade is always larger, resulting in a greater heating up of the interior. In this project we focus on the application in the façade cavity. (Knaack et al., 2018)

The term *glare* is understood as a disturbance of visual perception, which emanates from a too bright light source within the field of view. According to this definition, glare is caused by differences in brightness. The reason for this phenomenon is the adaptation of the eye. The perception from high to low luminance needs a certain amount of time, making it impossible to achieve perfect visual performance in the short-term. Nevertheless, a sufficient amount of daylight and visibility to the outside world is still required, which in particular favours the development of adaptive, selective sun and glare protection systems. (Haas-Arndt & Ranft, 2007; Hammer & Wambsganß, 2020; Knaack et al., 2018)

1.2 TEXTILE- AND FOIL-BASED MATERIALS

Compared to conventional façade materials, textiles and foils combine a particular lightness and flexibility with a clear design language, that predestines them to be used in dynamic façade systems. Textile fabrics create a unique aesthetic effect, that distinguishes them from other façade materials due to their haptic qualities, their translucency, their micro-structured surfaces, as well as their immense variety of colours, patterns, and structures. They therefore expand the visual design spectrum of the building envelope at the micro, meso, and macro scale. Notwithstanding the diversity of design options and techniques offered by textile materials, their scope of application in architecture has so far only been used to a limited extent. Consequently, target for the future will be "to leave the goal of wrinkle-free prestressed monochrome skin and to give textile building back the quality it has lost: that of a fabric." (Blaser, 1999)

Their minimal weight per unit area and their high mechanical strength open up a previously unexploited potential for their application in resource-efficient architecture. In this field, they offer both a ground-breaking expansion of the functional spectrum of the outer shell as well as a significant weight reduction of new and existing buildings. Considerable economic and ecological advantages can result in a fully multi-layer, textile- and foil-based enveloping system of flexible high-performance materials framed in a profile system, thereby creating an outer thermal building envelope, that fulfils all the requirements of a façade. (Haase et al., 2011a; Haase et al., 2011b)

1.3 ADAPTIVITY OF THE BUILDING SKIN

A very interesting way of designing textile building envelopes is the combination of aesthetic and functional qualities with the potential of varying the façade properties by implementing active components. Conventional façades due to their constant building physics and design characteristics can react only to a small extent to climatically varying outside conditions or changing user requirements.

Thus, the aim of our research is to develop adaptive building envelope systems whose properties are variable in terms of light transmission, energy reflection, and external appearance. The term *adaptivity* is here understood as the implementation of sensors and actuators which, in combination with an automated control unit, allow to react on differing environmental situations or user requirements in order to provide automatically or in a user-controlled manner the optimum interior and exterior conditions. The synthesis of an appealing design with the functionality of an adaptive adjustment enriches the architectural qualities of textile building envelopes. (Knaack, Klein, Bilow, & Auer, 2007; Sobek, Haase & Teuffel, 2000)

Due to the high individualisation degree of textile façades, a precise adaptability to strongly fluctuating requirements can be achieved by implementing active components, thus resulting in a significant increase of user comfort and a reduction of energy consumption. This allows to create new design elements, that emphasise the material-immanent properties of the textile, such as the soft, the folded, and the supple, by simultaneously integrating various functions, like a precise and systematic control of the daylight transmission values of the façade for example. (Zapala, 2018).

The Institute for Lightweight Structures and Conceptual Design (ILEK) is a pioneer in the field of textile construction, and has worked out, within the scope of various research projects (Haase et al., 2011a; Haase et al., 2011b; Bäumer, Haase, Mielert, Ocanto, & Schmid, 2012), the fundamental principles on the physical building measurement as well as ground-breaking research results on the design and construction of textile- and foil-based skins. In the following, the development of a textile-based, energy- and resource-efficient façade component for targeted sun and glare protection (PAOSS) is presented in detail.

2 PNEUMATICALLY ACTUATED ORIGAMI SUN SHADING

Conventional folding systems are opened by tensile forces acting on the periphery, but making it necessary to install additional cable structures on the façade. Investigations at the ILEK have demonstrated their opening and closing mechanism by the action of centrifugal forces (Sobek, Morgan & Bogdan, 2004). For this purpose, the folding structure is mounted on a centrally positioned electric motor, which generates the necessary centrifugal forces when rotated.

Meanwhile, this approach has been further developed towards a radial system, that can be opened and closed by one central activation source, only requiring a small amount of energy input into the system once, while creating two stable states by implementing active pneumatic components. The logic is similar to the one used in an air whistle. Through air pressure, the Origami elements unfold, while the restoring mechanism of the system is provided by an integrated spiral spring whose force causes the refolding.

During the day, the unfolded, opened structures reflect the irradiated solar energy and prevent the interior from overheating by a partial or full-surface regulation of light and radiation transmission. Individually activated single elements offer a targeted, selective glare protection, while at the same time ensuring the required daylight supply. In case of a clear night the heat radiation to the cold night sky and thus the cooling down of the building can also be influenced by these elements.

2.1 ORIGAMI GEOMETRY OPTIMISATION

The above-described pneumatically actuated sun and glare protection system is based on the Origami folding geometry “Starshade,” developed by the Origami artist R. Lang for astrophysical purposes of the American space agency (NASA). The original “Starshade” is applied to shade the brighter and thus glaring starlight during the exploration of unknown exoplanets in space. The transportation and positioning of the immense “Starshade” shading and glare protection elements in space requires a maximum compactness of their geometry in the folded state with a maximum reduction of their dead load as well. In this context, the Japanese Origami folding art was used to develop a space-saving, efficient, and lightweight system design, covering a surface of around 34 m diameter, which is characterised by a particularly high difference between its closed and open state. (Arya et al., 2017; Sigel et al., 2014)

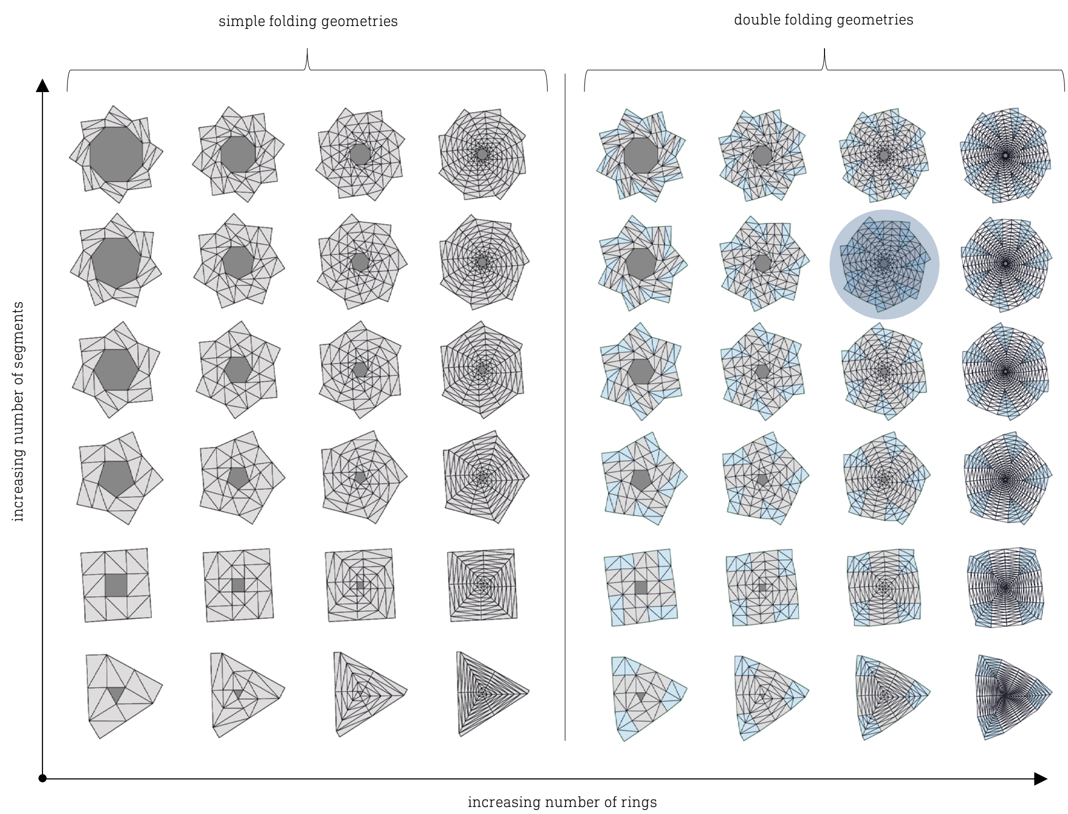


FIG. 2 Connotation of simple and double folding geometries. Copyright by ILEK

In order to be applied in the façade cavity of an ETFE cushion, the basic geometry of the "Starshade" has to be optimised in terms of the specific parameters of a minimum component depth with a maximum surface area difference between the closed and the open state, while at the same time reducing the complexity of the system as much as possible.

For this purpose, simple as well as double-shaped folding geometries were analysed in order to identify the most efficient folding geometry. The three main characteristics of a radial folding shape are: the folding type, the number of segments, and the number of rings. Fig. 2 represents variations of different folding geometries, obtained by varying these parameters at a constant outer radius of 50 cm.

An increasing number of segments leads to an expansion of the inner radius, while reducing its depth. Thus, an increasing number of rings causes a reduction of the inner radius, while expanding its depth. In order to keep better control of the rising complexity, the maximum was limited to eight inner rings. Double folding geometries are characterised by downfolded peaks (marked in blue) achieving a reduction of the structures depth and thus are identified to be more efficient in terms of a maximum surface area difference between closed and open state.

Respecting the restriction of a maximal component depth of 100 mm to provide the applicability of the PAOSS elements in all types of façade cavities, the most suitable folding geometry according to the parameters above is specified. With a structure height of 94.5 mm, an inner radius of 91.8 mm, and a difference of 0.613 m^2 between its open and closed state along with the outer radius of 50 cm, the folding geometry marked in the connotation (Fig. 2) above fulfils all the specific requirements. The resulting maximum switching difference of the system is approximately 82%.

2.2 MATERIAL ANALYSIS

The application of textiles and foils in the building façade depends on their UV resistance as well as on their sufficient fire protection quality. According to DIN 4102, at least B1 level (flame resistance) is required. In order to provide enough natural daylight illumination of the room even in a shaded state, the translucence of the shading material in terms of light transmission value may vary between 0 % and 40 %, depending on the type and thickness of the material (Zapala, 2018). Textile materials can be classified in the following three main categories: non-woven fabrics, woven fabrics, and knitted fabrics. (Sobek & Speth, 1993)

FIG. 3 Tyvek Material. Copyright by ILEK

FIG. 4 Airtex Super FR Material. Copyright by ILEK

The first prototypes of the PAOSS elements were made of perforated and folded Tyvek (Fig. 3), a flame-resistant, high-density polyethylene (PE) nonwoven fabric from DuPont de Nemours (Luxembourg) with a surface related weight of 120 g/m^2. After a few folding and unfolding cycles, the material tends to wrinkle as a result of the pneumatic actuation, which significantly interfere with the opening and closing mechanism of the structure.

In this context, paper-like Origami materials are not compatible with the pneumatic actuation of the system, since this method requires a textile material with a typical softness and flexibility. Further material analyses therefore concentrate on flexible, textile woven fabrics, in particular on technical composite textiles from PES with various coating techniques to guarantee the material-specific requirements as well as a low bending stiffness for their implementation in radial folding structures. Table 1 contains a selection of appropriate materials with their specific technical properties.

TABLE 1 Sun Shading Material Analysis (Bender, 2020)

NO SUN SHADING	VALMEX TF 400 F1	SOLTIS HARMONY 88	SUNWORKER	TEMPOTEST STARSCREEN	TWILIGHT METAL	AIRTEX SUPER FR	FIREMASTER
Material	PES	PES	PES/PVC	PES	PES/PAC	PES	PES/MAC
Coating	Vinyl		PVC	PTFE	Metal	PUR	Resin
Weight [g/m^2]	420	360	300	220	350	275	400
Thickness [mm]	0,77	0,45	0,42	0,52	0,5	0,35	0,6
Openness factor [%]	34	8	6	3,5	1,4	0	0
MEASURED SOLAR TRANSMISSION, REFLECTION AND ABSORPTION DATA (WAVE SPECTRUM 300 NM TO 2500 NM)							
T_{SOL} [%]	44,17	27,16	25,08	39,48	7,66	16,95	15,13
R_{SOL} [%]	51,75	67,14	68,56	54,32	42,08	74,65	71,91
A_{SOL} [%]	4,07	5,70	6,36	6,20	50,26	8,40	12,96
MEASURED VISIBLE TRANSMISSION, REFLECTION AND ABSORPTION DATA (WAVE SPECTRUM 380 NM TO 780 NM)							
T_{VIS} [%]	43,85	25,09	23,90	41,16	4,14	15,59	13,17
R_{VIS} [%]	51,50	73,62	76,19	57,72	37,68	82,95	78,44
A_{VIS} [%]	4,64	1,29	-	1,12	58,19	1,46	8,39

The pictures in Table 1 thereby give an impression of the visual appearance of the examined textiles. With an increasing openness factor, the transparency and the visual relation of the user to the exterior accordingly rises. A zero-openness factor implies a translucency of the material, which is sufficient in particular for selective sun and glare protection systems allowing a targeted view to the outside. In particular, a higher openness factor of the textile implies a lower degree of efficiency in terms of sun and glare protection. A lower material thickness leads to an advantageous, higher compactness of the structure in a folded state as well as to a maximum surface related weight reduction.

The evaluation of the material properties in the solar and visible range of radiation is a significant parameter for the selection of sun and glare protection materials. According to DIN EN 14500, the spectral radiation behaviour of textiles is measured by means of a spectrometer with an integrating sphere ("Ulbricht sphere"), whereas a distinction is made between the three following spectral parameters: reflectance (R_{SOL}, R_{VIS}), transmittance (T_{SOL}, T_{VIS}), and absorbance (A_{SOL}, A_{VIS}). For this purpose, empirical measurements were carried out in the photo spectral measuring device of the institute. Since the spectral data of textiles are influenced by the colour of the material, the textile samples have all been tested in the same colour (white), with the exception of the textile Twilight Metal, which is only available in silver. (DIN EN 410, 2011; DIN EN 14500, 2018)

The measurements were carried out both on the spectrum visible to humans within a wavelength range of 380 nm to 780 nm (VIS), considering the spectral brightness sensitivity $V(\lambda)$ as well as on a frequency range of 300 nm to 2500 nm (SOL), including the relative spectral radiation distribution S_{λ} according to DIN EN 410 Table 2. The frequency range includes the UV-B range from 280 nm to 315 nm, the UV-A range from 315 nm to 380 nm, the visible spectrum from 380 nm to 780 nm, and parts of the short-wave IR range from 780 nm to 2500 nm. The generated measuring data are listed in Table 1.

For a sun and glare protection system, the reflection coefficient should be as high as possible whilst the absorption coefficient should be as low as possible, in order to prevent heat radiation to the interior. Other advantages include a low visual transmittance T_{VIS}. To ensure sufficient daylight, while avoiding glare, an average value for T_{VIS} is recommended by $T_{VIS} \approx 10 - 15$ %.

Based on the photometric evaluation of the transmission, reflection and absorption properties of the appropriate textile materials via photo spectrometer, while also taking into account other parameters such as material thickness, surface related weight, UV-, and fire-resistance, the most suitable fabric was selected.

With a thickness of 0.35 mm, the polyester based and thermoplastic polyurethane coated Airtex Super FR (Fig. 4) is the thinnest, and with a weight per area of 275 g/m^2, one of the most lightweight among the above considered materials. Its surface structure is woven matt, whilst the fabric is UV-resistant and weatherproof. The textile has no openness factor and thus appears translucent. In addition, it is resistant to temperatures between -25 °C and +70 °C. According to the accomplished investigations, Airtex Super FR is identified to be the most suitable for the implementation in the PAOSS structures.

2.3 KINEMATIC FOLDING TECHNOLOGY

Depending on the respective material-immanent properties, in particular the material stiffness, appropriate digital and industrial manufacturing methods for a selective and specific functionalisation of the textile structure in order to generate the articulation effect were analysed. Dynamic folding elements are required to have both stiff properties in their planes and flexible qualities in the folding hinges.

Fig. 5 shows the investigated subtractive, additive, and mechanical/thermal methods. Subtractive methods include the abrasion of material in the folding hinges to achieve more flexibility. Additive methods foresee the application of thin layers to increase a local stiffness to a thin textile with low form stability, while adding no additional layers at the hinges to allow for the articulation.

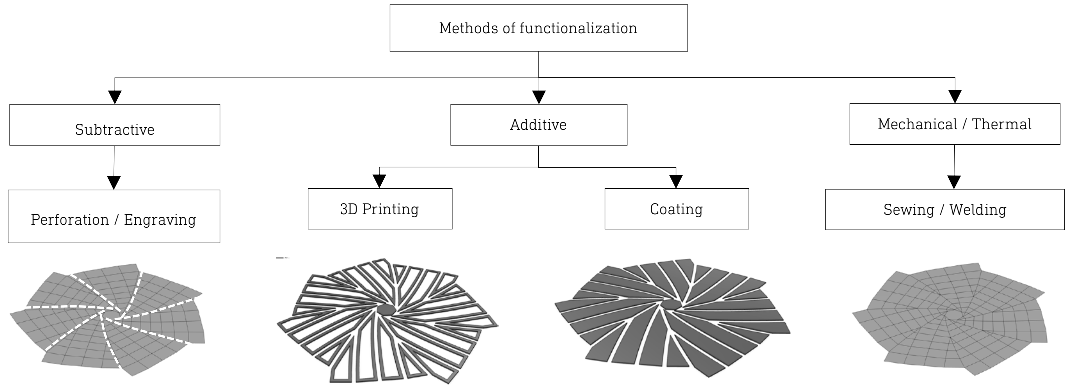


FIG. 5 Manufacturing methods to functionalise a textile folding structure in order to generate an articulation effect. Copyright by ILEK.

Mechanical or thermal processes, meanwhile, attempt to create a shape memory in the structure without applying or removing any material. Within experimental investigations, subtractive methods with a perforation or engraving of the hinges as well as additive textile 3D-printing or coating methods to precisely define the textile's stiffness were carried out. Additionally, the application of mechanical or thermal methods, such as sewing or welding, has been evaluated.

Subtractive methods such as thermal cutting techniques (laser or plasma cutting) prevent fraying edges by fusing the textile cuts, but often cause black or brown discolouration on the cut edges due to oxidation of the material. Mechanical techniques (cutting, plotting, water jet cutting, or punching) offer higher precision without edge finishing. Subtractive manufacturing methods are more suitable for stiffer materials. (Fahrenwaldt, Schuler, & Twrdek, 2014; Gries Veit, & Wulfhors, 2014; Lütke, Klotzbach, Wetzig, & Beyer, 2009; Machova et al., 2011)

The additive methods require a high flexibility and softness of the textile. Particularly for additive techniques, it is important to ensure the traceability of all individual components into the material cycle. This is why it is recommended to use additive skeletal structures via FDM (Fused Deposition Modelling), made of thermoplastic polymer, that can be applied in layers onto polyester materials, for example, and bond with the textile without impairing its recycling properties (Fig. 6). The biggest challenge in this context is the adhesion to the textile, making double-sided printing a viable option. (Deleersnyder & Ruys, 2015)

Partial coatings, applied in several layers at one or both sides of the material, prevent the angular twisting of threads in the woven fabric, thus generating a partial membrane stiffness. Besides this reinforcement, it is furthermore possible to obtain high-performance material properties such as heat resistance by means of additives and auxiliary ingredients. (Gries & Klopp, 2007)

Thermal and mechanical methods are appropriate for producing the articulation effect, as they provide the mountain and valley folds with an additional orientating shape memory (Fig. 7) in comparison to subtractive or additive manufacturing methods. Their succesful experimental validation was achieved for the textiles Airtex Super FR, Soltis Harmony 88, Sunworker, Firemaster. Preconditions for the thermal transformation of a polymer are thermoplastic material properties.

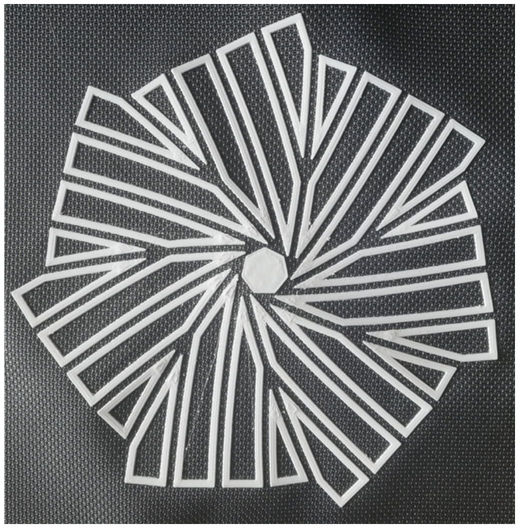


FIG. 6 3D-printed skeletal polymer structure on polyester fabric. Copyright by ILEK

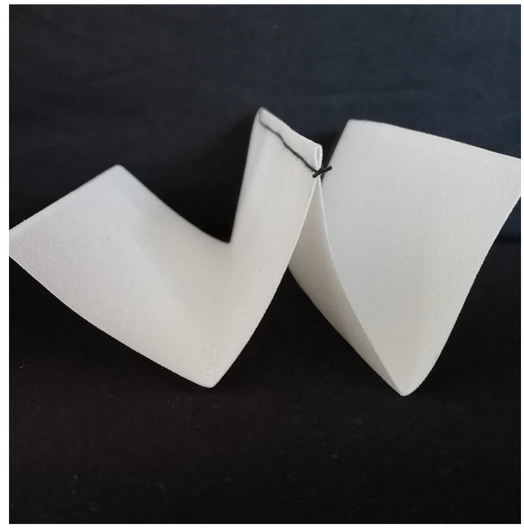


FIG. 7 Shape memory effect by sewing. Copyright by ILEK

Applying high-frequency radiation, heat, or electrical impulses, the molecules oscillate and, by means of mechanical pressure, are joined together at the folding edge to a water- and airtight weld seam. Sewn joints can be subsequently tightened up by welding or by injecting a coating to achieve an airtight lamination respecting all requirements for a clear material separability. The use of digital, automated production methods in general enables the folding structures to be produced with high precision in a fast and cost-effective way.

2.4 ACTUATION STRATEGY

The opening and closing mechanism (Fig. 8) of the PAOSS elements is carried out by special pneumatic actuators, that generate a deployment of the system via air pressure. An integrated spiral spring - without air pressure - provides the resetting effect of the system to its original state, similar to an air whistle. (Eisenbarth, Haase, & Sobek, 2019)

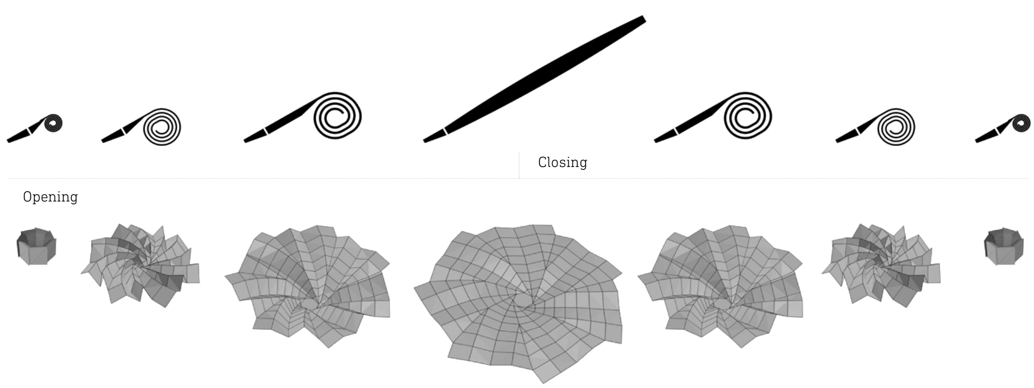


FIG. 8 Opening and closing mechanism. Copyright by ILEK

For the integration of the pneumatic actuators, additive and integral methods were investigated. The first prototypes of the pneumatic actuators were integrated additively (Fig. 9). For this purpose, the hermetically laminated one-piece woven pneumatic actuators by Jacquard weaving technology are fitted with the spiral spring inside and fixed to the PAOSS elements by thermal or mechanical joining techniques such as sewing, welding etc. at the back of the folding structure. The maximum number of additively applied actuators is limited by the connectivity of the air supply ducts.

From an aesthetic, functional, and economic point of view, the integral implementation of the actuators is of particular interest. In this way, considerably more actuators can be integrated to achieve a more homogeneous air distribution at equal manufacturing costs. Therefore, on the inside, the fabric has to be partially coated for airtightness and then laminated together to create airtight cushions.

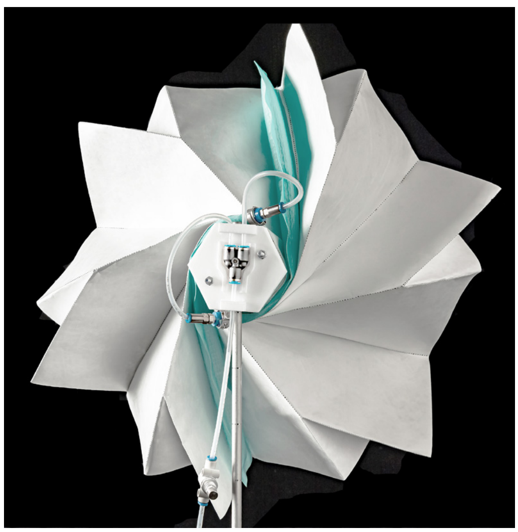


FIG. 9 Additively joined pneumatic actuators. Copyright by ILEK

FIG. 10 Connection joint for PAOSS elements. Copyright by ILEK

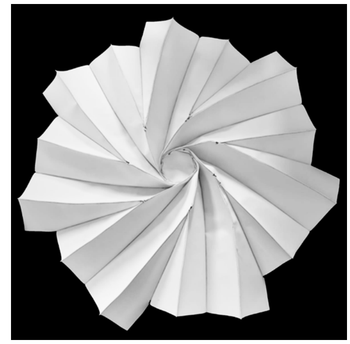
The supply is provided from the centre of the folding structure, wherefrom the air can be distributed to an unlimited number of segments. To integrate the spiral spring, a special channel is necessary in which the spring can be inserted and fixed. In order to connect the folding structures to the pneumatic lines and to enable air supply, special 3D-printed connection elements (Fig. 10) were developed, which can be used to fix the elements to the substructure e.g. to a steel cable net.

Table 2 shows the evolution from the first prototype to the final product in terms of folding geometry optimisation as well as material analysis and selection under consideration of the investigated kinematic folding technologies and actuation strategies.

The PAOSS are automatically controlled by detecting illuminance and glare in the room they are intended to shade. In case the light intensity increases or decreases to a defined level, the control unit transmits this information to selectively open or close the air supply of the individual actuators via adjustable valves to ensure sufficient daylight provision and to provide glare protection by individually adjusting single PAOSS. Manual control of the system by the building user is achieved for individual adjustment of the comfort requirements.

The prototypical implementation and development of the integral method for integrating the pneumatic actuators will be the subject of ongoing research activities in the context of the PAOSS structures and will therefore not be discussed further in this paper.

TABLE 2 Evolution of PAOSS



	FIRST PROTOTYPE	LAST PROTOTYPE
Depth [mm]	185	94,5
Difference open-closed [m^2]	0,422	0,613
Material	Tyvek	Airtex Super FR
Actuation	additive	integral

3 FUTURE OUTLOOK

The PAOSS elements are designed to be implemented as sun and glare protection in the façade cavity of a conventional glass double façade or in overpressure-stabilised ETFE cushion constructions. Focusing on maximum savings of material, mass, CO_2, and energy, their implementation in ETFE cushion constructions leads to synergies in the use of the pre-existing air-compressing infrastructure.

A prototypical realisation and application (Fig. 11, Fig. 12) is planned within the research projects described below: an ETFE cushion construction will be designed to be easily implemented in the standard profile system ETFE_THERM+ provided by RAICO. Here, the air supply is invisible, being integrated in the post and rail system. In order to generate an easy mounting and demounting of the PAOSS elements, a modular insert based on the RAICO profile system is developed, comprising a substructure to attach the individual elements together with the appropriate air supply hoses via the specially developed connection joints shown in Fig. 10. The substructure does not interfere with the light transmission or the visual connection out of the building, thus transparent glass grid constructions or filigree, prestressed cable net structures are suitable.

Within the scope of the project “Development of Adaptive Membrane Façade Modules,” funded by the research initiative Zukunft Bau of the German Federal Institute for Research on Building, Urban Affairs, and Spatial Development (BBSR), prototypes of the above described PAOSS elements will be investigated in terms of building physics and daylight performance as well as detailed from a technical-constructive point of view. Aim of the BBSR project is an integrative and comprehensive development of adaptive, modular, textile- or foil-based, multi-layered and multi-functional façade systems with envelope and profile, which considerably expand the façade functionalities as well as the design possibilities of the outer skin. The development includes the realisation of transparent, translucent, and opaque façade solutions at the site of the demonstrator high-rise building of the CRC 1244, where the resulting systems will be extensively monitored.

Considering the limited availability of natural resources, the Collaborative Research Centre 1244 (CRC 1244) at the University of Stuttgart, entitled "Adaptive Skins and Structures for the Built Environment of Tomorrow," outlines ways to minimise the use of material, resources, and energy with a maximum increase in user comfort by investigating the potential and applicability of adaptive building skins and structures. Within the CRC 1244, funded by the German Research Foundation (DFG), the world's first adaptive high-rise building (Fig. 12) is being constructed on the University Campus Stuttgart-Vaihingen (Weidner et al., 2018). The building is equipped with an extensive measuring infrastructure in the interior and exterior, thus serving as a platform for the investigation and demonstration of innovative adaptive building envelopes in order to verify their long-term suitability, reliability, and efficiency under real weather conditions at a scale of 1:1. In this context, the demonstrator high-rise building is predestined for the first prototypical implementation, evaluation, and validation of the PAOSS system in the above mentioned overpressure-stabilised ETFE cushion construction.

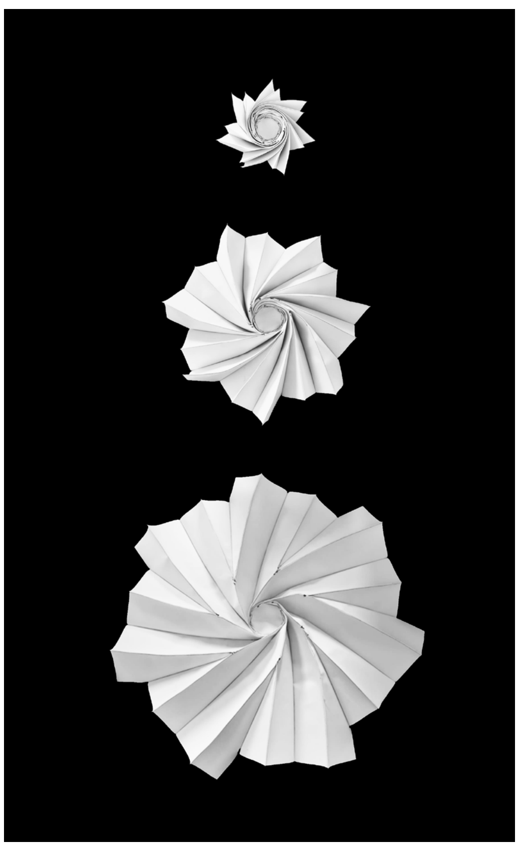


FIG. 11 Deployment of the PAOSS elements from a compact state (above) to an opened state (below). Copyright by ILEK

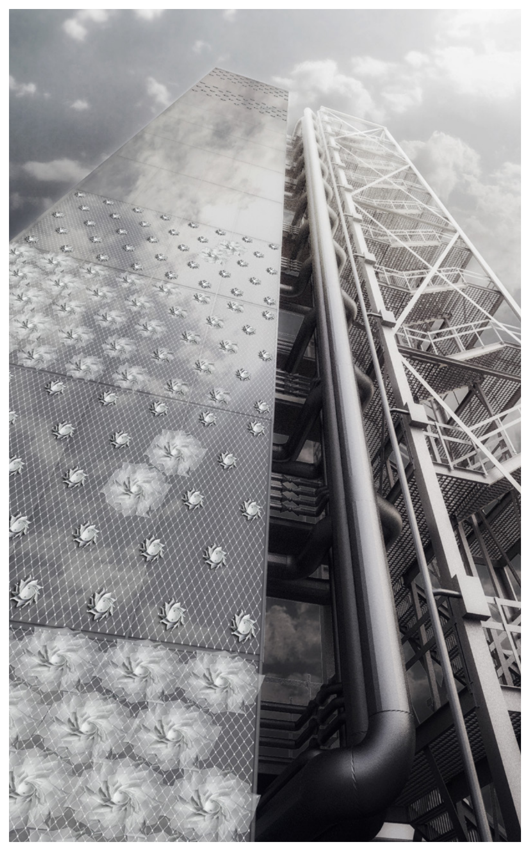


FIG. 12 Visualisation of the demonstrator high-rise building with adaptive membrane façades. Copyright by ILEK

4 CONCLUSIONS

In the context of the increasing transparency of our buildings and rising outdoor temperatures, notably in our cities, the importance of adaptive sun and glare protection systems has been clearly identified. The target is to achieve a selective or full-surface regulation of light and radiation properties in the building envelope in order to protect the interior from overheating without interfering with daylight supply. Therefore, a new lightweight, textile, pneumatically actuated, adaptive sun and glare protection system based on Origami folding has been developed. Applied in the façade cavity of ETFE cushion constructions, synergies of the pre-existing air infrastructure can be used for economical savings.

The geometry based on NASA`s "Starshade" Origami folding has been optimised in terms of a minimum complexity, a minimum component depth, and a maximum surface area difference between its closed and open state resulting in a maximum switching difference of 82%. Based on photometric measurements a UV- and fire-resistant, translucent, polyester-based, textile fabric with thermoplastic polyurethane coating could have been identified, that has a low weight per unit area of only 120 g/m^2. Among the conventionally available and suitable materials this textile offers the highest reflection coefficient in solar and visible range of radiation (R_{SOL} = 74,65 %, R_{VIS} = 82,95 %), a low absorption coefficient (A_{SOL} = 8.40%, A_{VIS} = 1,46 %), and an optimal visual transmittance of approximately T_{VIS} ~ 15 %. Subtractive, additive, and thermal-mechanical manufacturing methods for the functionalisation of the textile, e.g. to generate the articulation effect, were investigated. For thermoplastic polymer-based materials, welded or sewn, air-tightened seams are the most suitable, due to the resulting orientating shape memory effect of the mountain and valley folds.

This paper focuses on the integration of a simple, resilient, and low energy actuation mechanism as an alternative approach to the vast number of conventional adaptive solar and glare protection systems. Linked to the use of high-tech components, these are characterised by high complexity and susceptibility to defects, system failures, and obsolescence. Meanwhile, the use of simple, conventionally established actuation mechanisms such as the transfer of the functional mechanism of an air whistle into a new context opens up a low-cost and durable actuation method. Compared to the conventional electro-mechanically actuated systems, the implementation of pneumatic actuators to open the PAOSS in combination with an integrated spiral spring system to re-close offers an aesthetically and energetically optimised solution. Only a small amount of energy is required to be put into the system for the deployment, thus creating two stable states as well as a very smooth and elegant opening movement.

A further increase of the prefabrication level to a serial production, including the use of simple assembling techniques without any inseparable connections, leads to a modular system design, which due to the exchangeability, recyclability, and returnability of all system components into the material cycle, is lucrative in economic as well as ecological terms.

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