Applied Composite Materials (2022) 29:343–356
https://doi.org/10.1007/s10443-021-09941-8

Advanced 3D Textile Applications for the Building Envelope

Claudia Lüling[1] · Petra Rucker-Gramm[1] · Agnes Weilandt[1] · Johanna Beuscher[1] · Dominik Nagel[1] · Jens Schneider[2] · Andreas Maier[2] · Hans-Jürgen Bauder[3] · Timo Weimer[3]

Received: 13 May 2021 / Accepted: 9 July 2021 / Published online: 15 October 2021
© The Author(s) 2021

Abstract
Within the field of textile construction, textiles are traditionally used either as decorative elements in interior design or as flat textiles in tensile-stressed lightweight constructions (roofs, temporary buildings, etc.). Technical textiles made of glass or carbon fibers are now also used as steel substitutes in concrete construction. There, flat textiles are also used as lost formwork or shaping semi-finished products. Applications for 3D textiles and in particular spacer textiles have so far only been investigated as part of multilayer constructions in combination with other elements. Otherwise, there are no studies for their application potential in the roof and wall areas of buildings and as a starting structure for opaque and translucent components. The two research projects presented here, "ReFaTex" (adjustable spacer fabrics for solar shading devices) and "ge3TEX" (warp-knitted, woven and foamed spacer fabrics) illustrate for one thing the possibilities for using 3D textiles for the construction of movable and translucently variable solar protection elements in the building envelope. Otherwise they show how 3D textiles in combination with foamed materials can be transformed into opaque, lightweight, self-supporting and insulated wall and ceiling components in the building envelope. Both projects are designed experimentally and iteratively. The results are compared in a qualifying manner, the aim being not to quantify individual measured variables but to explore the development potential of textile construction for sustainable future components and to realize the first demonstrators. In the ReFaTex project, 1:1 demonstrators with different movement mechanisms for controlling the incidence of light were realized. In the ge3TEX project, 1:1 demonstrators made of three different textile and foam materials were added to form new single-origin composite components for ceiling elements. Both projects show the great application potential for 3D textiles in the construction industry.

Keywords Lightweight Architectural Design · 3D Textiles · Spacer Fabrics

✉ Claudia Lüling
clue@fb1.fra-uas.de

[1] Frankfurt University of Applied Sciences, Frankfurt 60318, Germany

[2] Institute of Structural Mechanics and Design, Technical University of Darmstadt, Darmstadt 64287, Germany

[3] German Institutes of Textile and Fiber Research Denkendorf, Denkendorf 73770, Germany

1 Introduction

Textile architecture is very often associated with tent structures. Design strategies as developed, for example, by Frei Otto [1] still dominate architectural thinking and discussions. These tent structures consist of single-layer textiles subjected to tensile stress, which only develop spatial qualities when combined with cables and compression bars. For some time now, a team of architects and engineers at Frankfurt UAS together with the DITF (German Institutes of Textile and Fiber Research Denkendorf) and other partners have been investigating in particular the new potential of multilayer, sandwich-like 3D textiles for building applications. Starting with the two main types of building element typologies—opaque wall and roof elements and transparent or translucent opening elements—one question focused on has been how to add value to 3D textile structures by combining them, for example, with foam. The aims of the accompanying "3dTEX" [2] and "ge3TEX" [3] projects are:

- to establish and improve fiber and foam materials in order to improve the structural and insulating behavior of the new composite of foam and fibers;
- to investigate appropriate textile technologies and geometries depending on the different applications in the building skin, e.g., wall and roof elements;
- to design and build lightweight, formactive building element demonstrators on a 1:1 scale.

The team is also exploring the specific, constructive-aesthetic possibilities for 3D textiles solar shading devices for partial transparent or translucent opening elements in "ReFaTex" [4]. The question to be answered is whether 3D textiles due to their individually adjustable material thickness offer spatially effective modification via still unexplored movement options with low energy input. Movement and time are thus integrated into the textile design as a fourth dimension. Accordingly, the focus is on movement mechanisms for opening and closing or for the control of viewing and incident light from spacer textiles with the aim of developing robust and low-maintenance components for facades. When closed, they can also temporarily reduce energy loss or the warming-up of the rooms behind them. Based on traditional solar protection systems such as shutters, venetian blinds and pleated blinds, the investigations with spacer fabrics show how these mechanisms when transferred to multi-layer textiles can open up the possibilities for daylight management control by moving the entire solar protection element (macro level) and activating the textile structure in itself and on the meso level.

2 Methodology

An empirical and experimental methodology was chosen for all of the research projects. At the beginning, experimental investigations with spacer textiles on a 1:1 basis were carried out and optimized by the research team in an iterative process involving student seminar papers and experimental student mock-ups (Fig. 1). The "SpacerFabric_Pavilon" showed for the first time the architectural potential of the combination of partially foamed 3D textiles, combined with the translucent and light-directing appearance of the 3D textile material. Based on this experience the research team followed two different paths: In terms of

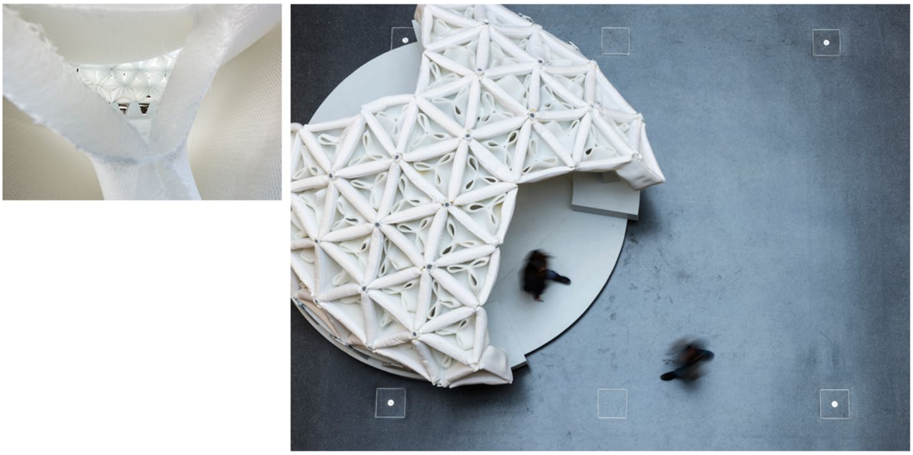

Fig. 1 Temporary pavilion made of foamed and folded spacer fabrics, “SpacerFabric_Pavilion”, left—view from the outside, right—view from the top. © Christoph Lison

solar-shading elements, the research project “ReFaTex” mainly involved the typological investigation of textile opening elements, based on existing solar shading devices. These traditional opening mechanisms were transferred to textile 3D geometries and modified accordingly in order to develop new options for controlling light incidence in buildings.

With regard to opaque building elements, the idea of foamed 3D textiles has so far been investigated in two projects, “3dTEX” and “ge3TEX”. In ge3TEX the full process was completed, from material formulations through to manufacturing techniques and the final design of building elements.Three material groups were selected together with the funding institution. The desired criteria were the possible fire resistance and recycling potential. Ultimately, new types of sustainable, foamed, textile composite components from one-single material group were identified:

- basalt fiber-based spacer fabrics in combination with cement foam;
- glass fiber-based spacer fabrics in combination with foamed glass from recycling resources (Fig. 2 shows the sequence of investigations carried out for this material group);
- spacer fabrics made from recycled PET-fibers in combination with PET-based particle foams, also from recycling material.

3 Results

3.1 3dTEX—Lightweight Wall Elements From Foamed Spacer Fabrics

In 3dTEX an initial understanding of the geometry of 3D textile structures was developed and concepts for relevant textile transformations tested, including for warp-knitted and woven 3D textiles. Figure 3 shows both textile technologies. On the left, a foamed warp-knitted spacer fabric becomes a framework-like wall structure with loadbearing and insulating areas. The unfoamed warp-knitted 3D textile is shown on the right side. The

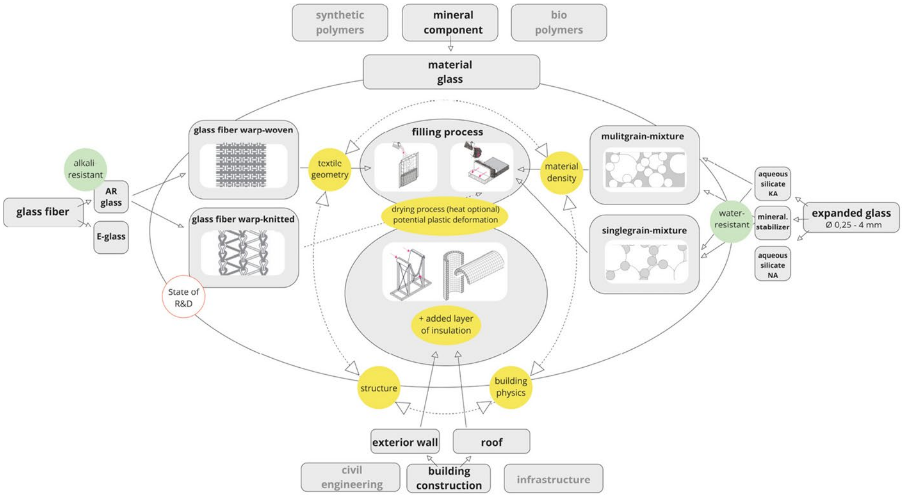

Fig. 2 Research methodology using the example of the development of foamed textiles made of AR glass textiles in combination with a filling of expanded glass with water glass. © Frankfurt UAS

focus was on the development of appropriate textile geometries for two-layer or three-layer textile elements, depending on the chosen textile technologies. Below right is an initial idea for a three-layer woven structure, designed and produced at the DITF [5]. The lower area of the three-layer fabric was foamed, while the upper area remained unfoamed for ventilation. In this way the three-layer textile was transformed into a ready-made, rear-ventilated, insulated wall element, able to absorb tensile and compressive forces at the same time. Bending tests and others were not conducted during this phase.

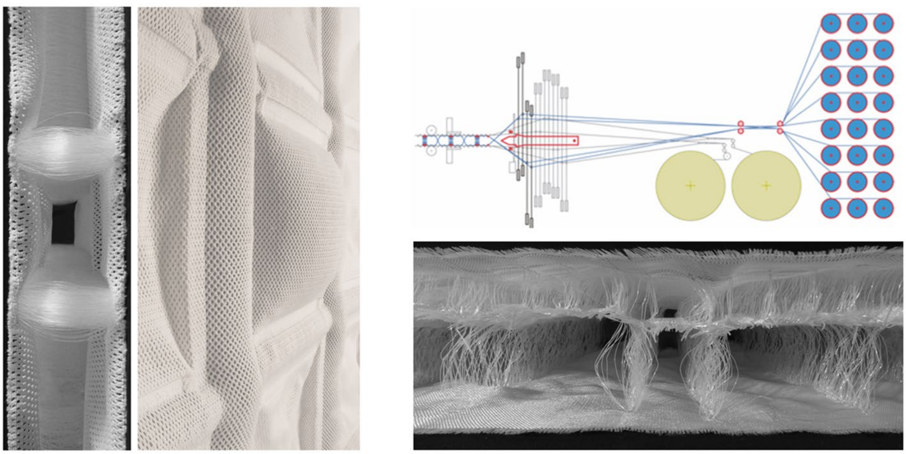

Fig. 3 The “3dTEX” research project (textile based, foamed wall elements): left side, warp-knitted and foamed spacer fabric; right side, spacer weaving machine with lancet technology and tangential withdrawal of the spacer threads from the creel and three-layer, woven spacer fabrics. © Frankfurt UAS and DITF

3.2 Ge3TEX—Warp-knitted, Woven and Foamed Spacer Fabrics for the Building Envelope

During the initial studies in 3dTEX, PU foams and PE fibers were used [6, 7]. The main objective was to identify the deformation behavior of the different spacer fabric types. Subsequently, further research was conducted in a follow-on project, ge3TEX, which focused on the enhanced materialization and sustainability of the new "fabricfoam" composite elements. High recycling potential and fire-safety building aspects were additional criteria. The decision was taken to use two mineral- and one polymer-based combination of fibers and foams, each from a single material background. The use of foamed materials such as cement foam, expanded glass and PET foams made from recycled material results in very different bonding properties with the corresponding basalt fibers, glass fibers and rPET fibers. It also results in different filling methods, which again led to the design of individual geometries for each demonstrator from each material group. Figure 4 shows the correlation between the parameters of textile 3D structures and the filling options. Ultimately, the aim is not the quantification of individual measured variables, but rather the comparison of components of different, single-origin material groups with the same functionalities and the implementation of the first demonstrators in order to develop new, formwork-free manufacturing techniques.

3.2.1 Basalt Fiber-based Spacer Fabrics in Combination with Cement Foam

A large number of tests had to be carried out to show whether the combination of foam and fibers had the potential to become a building component. Together with the industrial partner involved, the basalt rovings were individually poured into the cementitious foam matrix and tested for alkali resistance in accordance with DIN EN ISO 2062 and for damage in accordance with DIN EN 14,649 (SIC test). The manufacturer's cementitious foam has a density of 180 kg/cbm. The adhesion of the individual rovings was also checked in pull-out tests. These rovings were cast into the cementitious foam according to the subsequent position of the pile threads between the cover layers and in the cementitious foam. In addition, the rovings were woven into single-layer textile fabrics. Their adhesion was investigated in peel-off tests according to the subsequent position of the cover layers on or next to the cement foam. Filling tests were only carried out with woven fabrics due to the rather fluid structure of the cement foam. Knitted fabrics are too porous and elastic to be used as lost formwork. Finally, first demonstrators were produced. To summarize:

- Special alkali-resistant and processable basalt rovings were developed for ge3TEX.
- The new rovings were used first of the first time all to produce spacer fabrics at the DITF, (Fig. 5).
- The adhesion of the new rovings to the cement foam was proven, but not the adhesion of the single-layer woven textile surfaces made from them; knitted textiles in contrast displayed excellent adhesion. As a consequence, the woven spacer fabrics were modified in such a way that loops formed on the inside of the spacer fabric leading to sufficient mechanical adhesion (Fig. 5).
- Due to the low density of the cement foam, it can only be used for insulation purposes. For lightweight, pressure- and tension-stable insulated components, geometries have been developed for initially single- and subsequently double-curved cushion structures made of basalt fabric. The cement foam cushion structure then serves as lost formwork

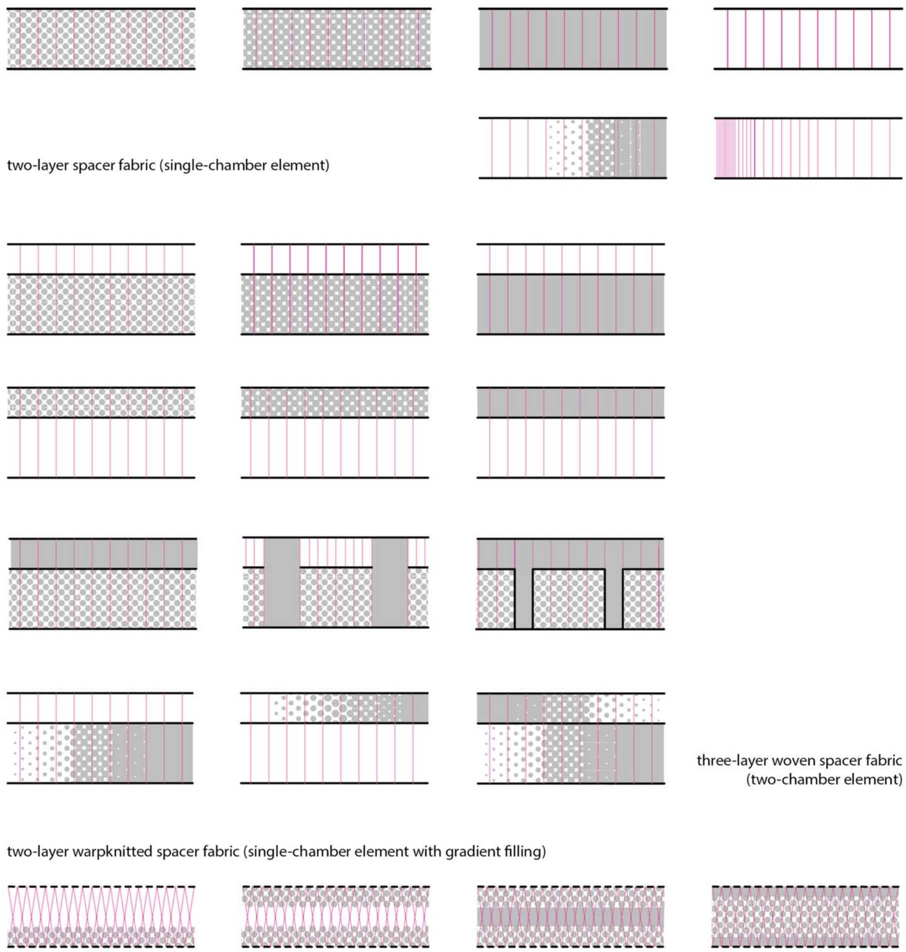

Fig. 4 Foamed spacer fabrics used as a "lost formwork": A formwork that stays in place, defines the surface quality but can additionally also be used for the transmission of tensile forces. © Frankfurt UAS

for an ultra-high performance top concrete layer. This results in a concrete-ribbed structure which is also supported horizontally underneath by the layer of filled basalt textile in the area of the crossing points. Production of the basalt spacer fabric includes reinforcement of the lower layer, which is strengthened in the area of tensile stresses (Fig. 6)

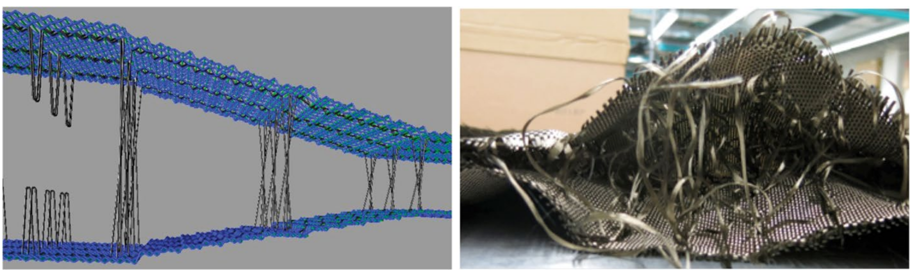

Fig. 5 Basalt fiber spacer fabric – woven. © Frankfurt UAS

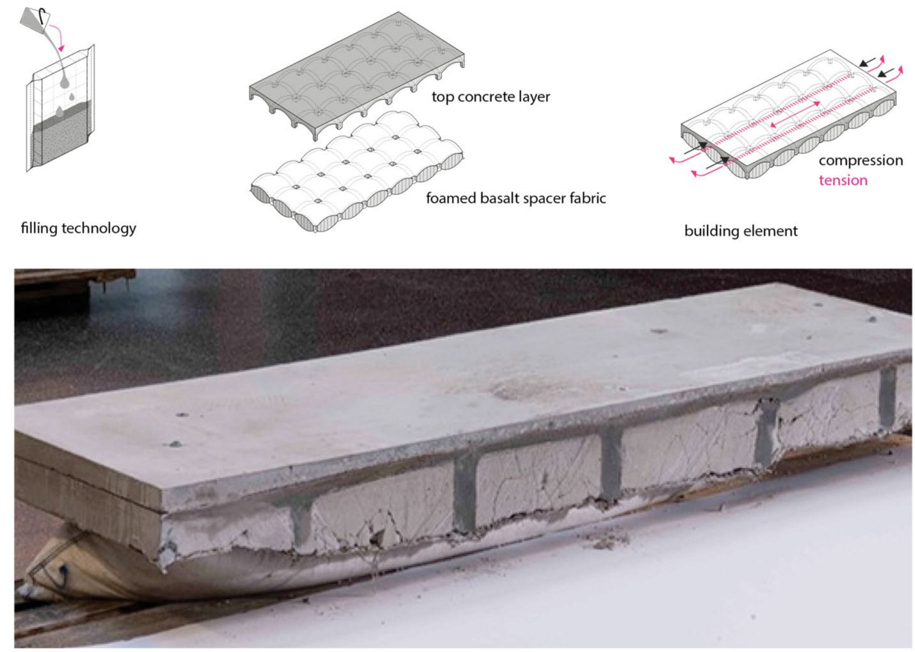

Fig. 6 First demonstrator: Formactive composite building component made of ultra-high performance concrete (UHPC), with lost insulation formwork made of basalt fiber spacer fabric, formed by a cement foam filling. © Frankfurt UAS

3.2.2 Glass Fiber-based Spacer Fabrics in Combination With Foamed Glass From Recycling Resources-

Expanded (foamed) glass made of recycled material can be bonded either by sintering (energy-intensive, in-situ unsuitable) or by using a suitable matrix to form a pore-based filler for filling spacer fabrics. Water glass was chosen as the development matrix, since the recycling objective for the new fabric-foam composite is the use of single-source materials. In contrast to the existing formulation for the cementitious foam, existing standard formulations for the production of waterproof expanded glass and water glass mixtures had to be tested and adapted for ge3TEX. The aim of the tests was to develop a processable, as light as possible, but equally pressure-stable expanded glass/water glass mixture—or to provide a number of formulations that are partially available for filling depending on the textile geometry and load case or insulation requirements (Fig. 4). The test series had the following parameters: density of the expanded glass granules, mixing ratio of the water glass and mineral hardener, drying temperature, drying time and waiting time until the mechanical and structural parameters are tested.

As with the basalt rovings, pull-out tests, peel-off tests and adhesive pull tests were also carried out with the glass rovings. In addition, the strength of the formulation was tested again after prolonged exposure to water. In contrast to the rather liquid, cementitious foam, the expanded/water glass matrix has a mortar-like structure. Filling tests were accordingly carried out with woven fabrics from the side and knitted fabrics over the cover layers. To summarize:

- Unlike with basalt rovings, all commercially-available E-glass rovings can be processed. Only two showed strong filamentation and are not suitable for the warp or for use as pile threads.
- The adhesion of single-layer fabrics made of AR glass was achieved satisfactorily through pre-treatment and impregnation of the fabric. It can be improved through mechanical adhesion as needed depending on the textile geometry of the top layers and the texturing of the pole threads.
- Structurally-dense mixtures as well as single-grain mixtures of expanded glass with different grain sizes were tested – the former on the assumption that they require less binder, because the spaces between them are filled by the smaller grains themselves rather than by the binder. The result shows that the optimized, dense mixture shows no added value in terms of strength and water glass content compared to a single-grain mixture of the same density.
- The mortar-like structure of the expanded water glass mixture enables warp-knitted spacer fabrics to be filled by squeegeeing the mixture over the cover surfaces (Fig. 7 - above center). The filling of an initial PE warp-knitted spacer fabric and subsequent drying over a mold showed very good results (Fig. 7—below right). Research

Fig. 7 Composite building component made of expanded glass in combination with lost formwork made of glass-fiber spacer fabric; below left - woven spacer fabric; below right - formactive warp-knitted spacer fabric. © Frankfurt UAS

is still underway into the production of warp-knitted spacer fabrics made of glass rovings. For reasons of processability it will probably not be possible to produce a stable pile yarn structure with the resilience needed for the squeegeeing process from glass rovings – a disadvantage as regards the desired monomateriality.

- For the first time, woven spacer fabrics made of AR glass were manufactured for the production of final demonstrators

3.2.3 rPET fibre-based spacer fabrics in combination wit rPET particle foam

Corporate partners were integrated into the project who manufacture space textiles from PET recyclate and PET particle foam from recyclate. Both products can also be returned to the recycling chain. Together with the partners, both the PET tapes and the selected PET particle foam were developed further (Fig. 8).

Two PET tape or strapping materials (standard material A and new material B with improved adhesion options) were tested as textiles A and textile B with standard particle foam A and with a likewise newly-developed particle foam B with greater expansion capacity. For the test, PET pouches were alternatively filled with unfoamed and pre-foamed beads and the expansion behavior and the fusion of the expanded beads with each other examined in different processes (oven, microwave, infrared, radio wave). In addition, two different adhesives were used to help the particles adhere to each other - a hybrid coating and an adhesive coating more appropriate for the planned mono-material. To summarize:

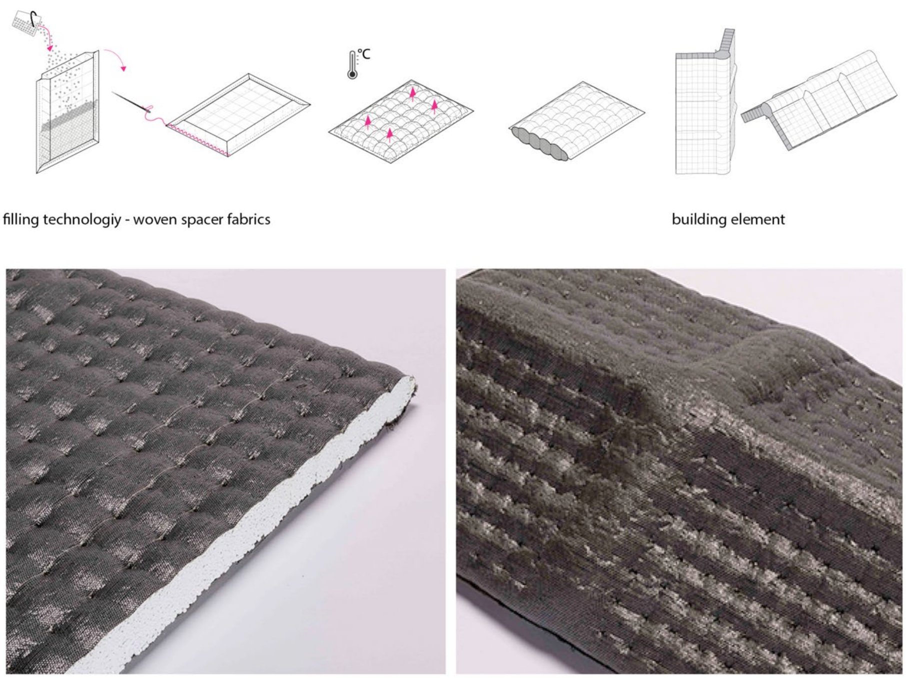

Fig. 8 Composite building component from expanded rPET particle foam in combination with lost formwork from rPET fiber—woven spacer fabric; left—planar element; right—self-foldable, formactive element. © Frankfurt UAS

- The shrinking behavior of the PET textile has a positive effect compared to the expanding particle foam. In various test series the optimal filling volume in relation to the shrinking textile volume was determined. All combinations of textiles A and B with beads A and B were tested. The new beads B are optimal, and the adhesion to the textile itself works best when using textile B.
- In further test series with and without pre-foaming, robust fusion of the foamed beads with each other was not achieved. Only by using an adhesive coating, which is added to the unfoamed beads, is it possible to produce a cut-resistant foam material from the foamed beads in a one-step process (Fig. 8).
- The particle foam expands in the spacer fabric. The textile thus serves as a shaping element for the expanding material; planar as well as formactive folded shapes were realized.

3.2.4 G3TEX - Results

In terms of opaque, self-supporting and insulating building components for the building envelope made from fabric-foam from three different material groups, Fig. 9 shows the advantages and disadvantages in each case and for the developed individual building elements, differentiated in terms of.

- recyclability
- weight
- global-warming impact

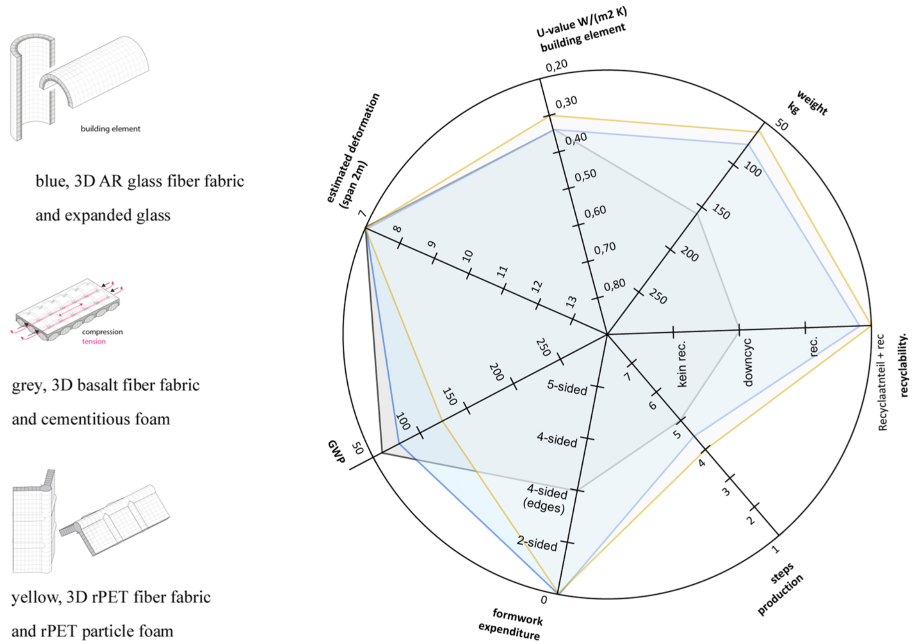

Fig. 9 Comparative presentation of 3D textile-based, foamed building elements, made of single-origin materials; all elements have comparable insulation values and deformation values. © Frankfurt UAS

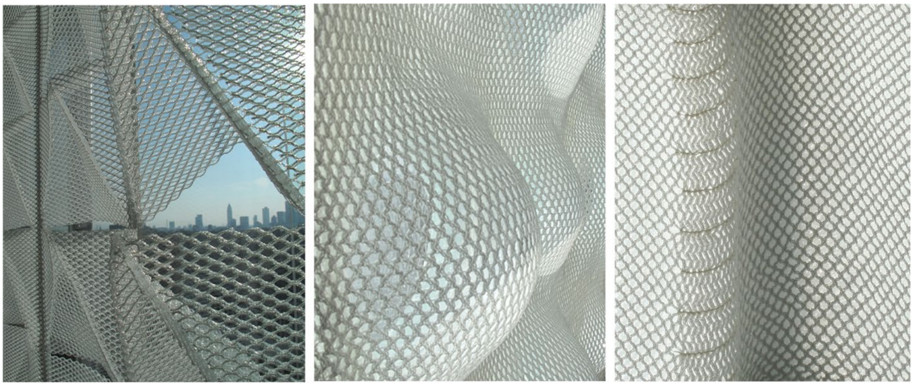

Fig. 10 ReFaTex—shading devices made of warp-knitted spacer fabrics. © Frankfurt UAS

Also part of the studies are lowest-possible transport volume, formwork dispensation, easy in-situ production and reduction of the process steps through use of highly functional semi-finished technical textiles. The results so far are very promising.

3.3 Adjustable 3D Textiles—ReFaTex

Ge3TEX looked into the question of opaque 3D textile-based, lightweight building elements for the building envelope. In contrast, the “ReFaTex” project deals with 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 "ReFaTex – reversibly foldable, energetically-effective 3D textiles in the building sector" research project, which focused on the production of ultra-light and stable elements from spacer textiles in the facade area that were also to be foldable and, depending on requirements, opaque and partially translucent or transparent. In the course of the research, the term "foldable" was replaced by "movable" in order to comprehensively capture the dynamic potential of spacer textiles. The following figures show the different results from the project. Figure 10 shows first mock-ups, Figure 11 shows first concepts and Figure 12 shows how the strategies could be used in a building context.

With regard to light-directing and controllable transparency, three mechanisms with a high potential for further studies were identified—folding, bending/compressing and stretching. 3D

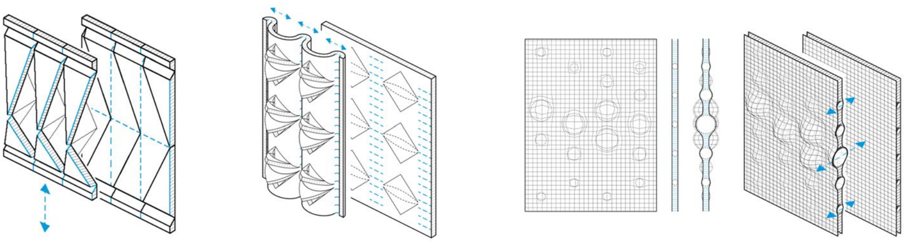

Fig. 11 ReFaTex, solar shading devices from spacer fabrics—folding, bending and stretching strategies to improve daylight control. © Frankfurt UAS

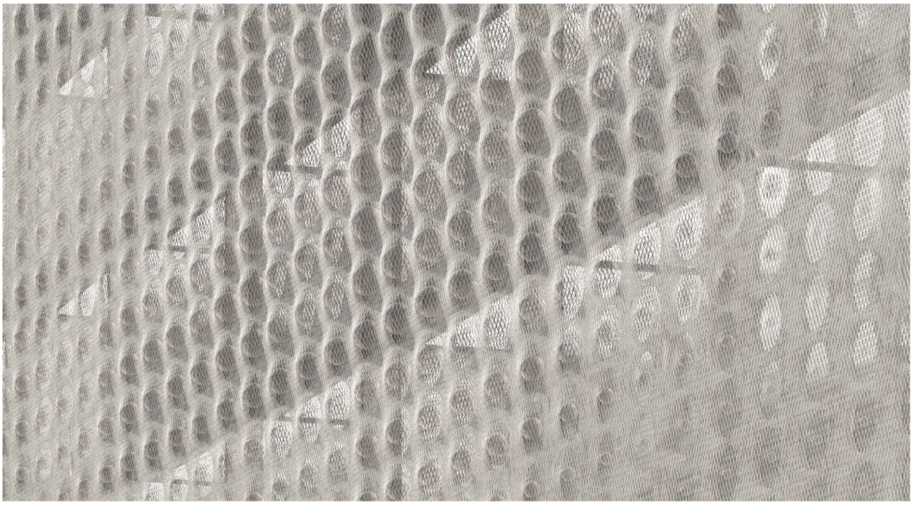

Fig. 12 ReFaTex, spacer textile, selectively stretched and in line with sunlight in real time with the help of internal pneumatic mechanisms. © Frankfurt UAS

textiles offer options for hingeless joints, achieved with partial incisions. New pleated structures can be created, which can also be used as external solar protection. To this end, the stability of the textile is increased by partial fillings as developed in Ge3TEX. Further applications are currently being developed for window shutters, lift-up shutters and folding shutters as well as pleated blinds in other geometries. Naturally, fabrics are subject to "soft wrinkling", and therefore the subject of bending mechanisms is valid. The elements realized so far appear to be much more "material"-like and softer than the folding structures. On the meso level, the bending of the spacer textiles results in the texture of the inner surface layer being automatically compressed or condensed. The bending movement can be used to selectively adjust areas with translucency (Fig. 10, right).

Fig. 13 6dTEX, 3D printing on 3D textiles, Frankfurt UAS together with ITA Aachen. © Frankfurt UAS

Consequently, on the macro level this means that the entire element must be correspondingly larger than the opening element. As a whole, the new elements resemble a thick, translucent curtain. Moreover, warp-knitted spacer fabrics can be stretched due to their mesh structure. Just as when the textiles are bent, the stretching movement changes the translucency. The elongation of individual, pile-thread-free textile areas perpendicularly to the cover surfaces was also investigated and resulted in a bubble-like solar shading device (Fig. 12). The next step is the development of a robust coating for all elements for cleaning reasons. All the systems are protected.

4 Conclusions

Spacer fabrics offer advanced 3D textile applications for the building envelope. Frankfurt UAS's projects demonstrate new options for sustainable, lightweight and highly functional building elements for the future. Further tests must be undertaken to improve the mechanical and physical properties of the composite materials and thus the functionality of the new composite components, depending on the individual application. In addition, further material combinations of fibers and foams will be investigated at Frankfurt UAS, for example based on renewable raw materials. With regard to ReFaTex, the light transmission values of the different shading devices are still being measured and support from the textile industry is needed to help with the different surface geometries of the spacer fabrics. In the "6dTEX—3D printing on 3D Textiles" follow-up project (Fig. 13), further investigations will be made with the aim of realizing "Architecture Fully Fashioned" in the future. Fully fashioned refers to a textile production technology in which all the parts of an item of clothing are produced in one integrated production process, so that it is ready to wear the moment it leaves the machine. Fully fashioned in an architectural sense implies a highly prefabricated textile lightweight envelope with minimal installation work on the building site.

Acknowledgements This paper and the research behind it would not have been possible without the exceptional support of the "Zukunft Bau Forschungsförderung" of the Federal Ministry of the Interior, Building and Community. It also would not have been possible without the enthusiasm, knowledge and attention of my colleagues at Frankfurt UAS including Prof. Dr.-Ing. Petra Rucker-Gramm, and the Laboratory for Building Materials, Building Physics and Structural Conservation including Dominik Nagel, my colleague Prof. Dr.-Ing. Agnes Weilandt, our research assistants, in particular Johanna Beuscher, and all the students who helped us. Last but not least, my thanks go to the German Institutes of Textile and Fiber Research Denkendorf including Dr. Hans-Jürgen Bauder and his team, and the Technical University of Darmstadt including Prof. Dr.-Ing. Jens Schneider and his research team, in particular Andreas Maier. Furthermore, the work would not have been possible without the extraordinary support of our many industry partners, to whom we once again wish to express our gratitude.

Funding Open Access funding enabled and organized by Projekt DEAL. "3dTEX" and "Ge3TEX", Federal Ministry of the Interior, Building and Community, Germany "ReFaTex", IFOFO funding, State Chancellery of Hessen, Germany.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Meissner, I.: Frei Otto - A life of research, construction and inspiration. DETAIL, Inst. für Internat Architektur-Dokumentation (2015)
2. Lüling, C., Richter, I.: Architecture Fully Fashioned - Exploration of foamed spacer fabrics for textile based building skins. J. Facade Des. Eng. **5**, 77–92 (2017) https://doi.org/10.7480/jfde.2017.1.1526
3. Lüling, C., Rucker-Gramm, P., Weilandt A., Beuscher, J., Nagel, D., Schneider, J., Maier, A., Bauder, H.-J., Weimer, T.: Ge3TEX – Multifunctional Monomaterials Made from Foamed Glass-, Basalt- or PET-based 3D Textiles. Powerskin Conference Proceedings S. 37–51 (2021)
4. Lüling C., Beuscher, J.: 4dTEX – Exploration of Movement Mechanisms for 3D-Textiles Used as Solar Shading Devices. Powerskin Conference Proceedings S. 159–172 (2019)
5. Bauder, H.J., Wolfrum, J., Gresser, G.: Entwicklung von textilen Mehrlagenstrukturen mit optimierten Fachwerkkonstruktionen für mehrfach gekrümmte Bauteile. IGF. 17409 (2015)
6. Schäfer, K., Nestler, D., Jahn, K., Jentzsch, H., Kroll, L.: Lightweight potential of 3D endless fiber reinforcement of polyurethane foam cores with spacer fabrics in hybrid sandwich structures with fiber reinforced thermoplastic facings. In: Hausmann, J.M. (ed.) Key Engineering Materials (2019)
7. Schäfer, K.; Valentin, S.; Meier, B.; Roth, I.; Helbig, F.:Verbundvergleich von hart mit weich – Leistungssteigerung rigider PUR-Hartschäume durch weichelastische 3D-Gewirke Kettenwirk-Praxis - Technical Textiles (2014)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.