Architecture Fully Fashioned – Exploration of foamed spacer fabrics for textile based building skins

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Abstract

"Architecture Fully Fashioned" is about lightweight design and new textile based building skins. Fully fashioned refers to a textile production technology wherein all parts of a piece of cloth are produced in one integrated production process, ready to wear the moment they leave the machine. Fully fashioned in an architectural sense implies a light, highly prefabricated textile envelope with minimum needs of installation work on the building site.

To develop these new textile powerskins, experimental student works and applied research projects at Frankfurt University of Applied Science investigate the potential of the combination of textile technologies with foaming technologies. This paper focuses on so called spacer fabrics and a research project called 3dTEX, founded by Zukunf Bau, where wall elements from foamed spacer fabrics presently are under development. The aim of the paper is to present 3dTEX within the context of the accompanying experimental student design works and to show the so far achieved results for a prefabricated, lightweight, self-supporting and highly insulated foamed textile skin, with reduced needs of installation work on the building site. This has been achieved by using the spacer fabric as lost formwork and using 3d-textile technologies, so as woven or warp-knitted spacer fabrics, in order to receive complex geometrical sandwich-like textiles. Together with the foam they become FabricFoam©. The new selfsupporting building elements not only offer possibilities for complex architectonical geometries including loadbearing structures, but also a wide range of surface designs in terms of structures, colours and additional functionalities. The focus of 3dTEX is on the development of appropriate textile geometries for one-layer or two-layer textile elements, depending on the choosen textile technologies. Foamed, they become lightweight, insulated elements, where the two layer textile can even be transformed into a ready-made, rear-ventilated, insulated wall element made from gradient fibre and foam material, able to absorb tensile and compressive forces at the same time.

The challenge for 3dTEX is to close the knowledge gap about what kind of textile technology can produce the envisioned textile geometry with which kind of fibre material. Further, 3dTEX research is about the appropriate, possibly in-situ, foaming technology and foam material, so that fibre and foam materials match as an aesthetic architectural element and in terms of mechanical and building physics as well as in terms of grey energy and recycling aspects.

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ZukunftBAU

1 INTRODUCTION

"Architecture Fully Fashioned" focuses on research carried out on textile facade constructions, especially on so called spacer fabrics, in combination with foams. Inspired by the fibrous and spongy structure of reeds like typha, foamed fabrics (FabricFoam©) combine fibres or textiles with foams or porous construction materials to be used e.g. for prefabricated, insulated and self-supporting lightweight building and facade elements, so as wall and/or roof elements.

The initial results of research into these issues will be presented below, concentrating on 3dTEX, a lightweight textile wall element, which is funded by the "Zukunft Bau" research initiative. It investigates the transfer of three-dimensional textile techniques and textile joining technologies for applications in facade and lightweight wall elements. The research focuses particularly on spacer fabrics: These are multi-layer, interconnected textiles produced in one work process, whose surfaces are linked by pile threads at a specifically defined distance. By arranging and spacing their textile layers and combining them with other materials, spacer fabrics can potentially integrate into and fulfil an exterior wall element's main functions, such as insulation and load-bearing, by making use of their structural cavities. In the 3dTEX research project, geometric textile structures for lightweight wall elements in building envelopes will be designed and planned and, taking the different properties of materials into account, the structures will be filled with foam to become demonstrators on a 1:1 scale (Fig. 1). They are then subjected to structural physics and load-bearing tests. The textile elements are not only the main functional components, they also determine the inetrior und exterior design of the envisioned facades. Project partners include ITV Denkendorf and Essedea GmbH & Co. KG.

FIG. 1 3dTEX: Spacer fabric, filled with foam, FFin / ITV Denkendorf, ©FFin

Textiles and foams are more than materials, they are also production technologies and can integrate different groups of materials. When used as composite materials in construction, they offer solutions for absorbing tensile and compressive forces, have good insulating properties and, as potential mono-materials, could be a recyclable alternative composite material for the high-performance powerskins of the future. Depending on a project's structural and climatic requirements, various textile fibres and technologies (weaving, knitting, braiding etc.) can be combined with different kinds of foams. Possible combinations include natural fibres with lignin, linseed oil or cellulose-based foams or glass fibres with foam glass or basalt fibres with foamed concrete, which is part of the 3dTEX research.

Transferring textile production processes to construction also offers the possibility of using alternative integral joining techniques. The term "fully fashioned" used in the context of knitting manufacture refers to the production of seamless pieces of cloth in an integral, industrial process that can dispense with the additive process of putting together single pieces of fabric to form a whole garment (Issey, Fujiwara, & Kries, 2001). The first "tailored" textile structural components for the construction industry have been created for use in load-bearing structures like woven fibre-reinforced 3D structures in T, L and I forms (TEXDATA International, 2015) and the vision for the future is towards "fully fashioned" building envelopes, that would make additive manual work on building sites unnecessary. 3dTEX in this context looks into the development of the design and building of fully-fashioned, self-supporting, insulated, one or two layer textile based facade elements.

2 METHODOLOGY AND STRUCTURE

3dTEX is an applied research project, so research and experimental works alternate and the approach involves the construction of demonstrators on a 1:1 scale, working together with project partners and interested companies. This paper will describe the still ongoing development of lightweight wall elements made of foam filled spacer fabrics, which are currently being developed in methodologically progressive work steps.

In a first step, involving masters architecture students, experimental pavilions and micro spatial structures were designed, built and evaluated like the SpacerFabric_Pavilion 2016 (winner of the Campus Competition Award 2016). The goal was to find out what structural load-bearing potential foam filled textile structures have and what design options they might offer. (see chapt. 3.1/4.1)

A second step, focused on identifying and evaluating comparable construction structures and products, including product developments and findings from research into technical textiles and foams. (see chapt. 3.2/4.2)

In a third step, potentially promising commercially available spacer fabrics technologies for initial prototypes were identified and these spacer fabrics were foamed.(see chapt. 3.3/4.3)

The fourth step involved designing and producing the first spacer fabrics made explicitly for the project, so that an attempt to foam custom-made fabrics could be made. Easily handled in-situ construction foams were initially used for the first demonstrators. These demonstrators were then subjected to a first series of comparative tests of their thermal insulation values, moisture absorption, behaviour in fire and load-bearing capacity. An ordinary, commercially available sandwich element was used as a reference structural component. (see chapt 3.4/4.4)

In parallel, materials research into fibre and foam materials was listed and evaluated in diagrammatic form, in order to identify an optimal material combination with a differentiated load-bearing and insulating structure for a recyclable, textile-based lightweight wall element. (see chapt 3.5/4.5)

The final steps now under way are the design and production of spacer fabrics and their foaming with the help of industriel partners. The aim is to finish the project with comparative tests of mechanical and building physical properties and evaluation of their façade design options.

3 EXPERIMENT/RESEARCH

The following chapters show step by step the approach and research towards lightweight textile building skins made from foamed fabrics, as been described above.

3.1 EXPERIMENTAL PAVILIONS AND MICRO SPATIAL STRUCTURES

Investigations into the experimental pavilion structures built by the students showed, how fibres and foams function as a composite and how they could be used to make architectural envelopes. The students worked with three-dimensional textiles such as textile sleeves or spacer fabrics, although structures independent of prefabricated 3D-textiles were also designed in the first phase. Figure 2 shows initial approaches to creating wall elements from fibres and foam. "MaschenSchaum" (transl.: Knit Foam), see Fig. 2 left, uses foam filled textile sleeves as lost formwork, while textile bands in "KugelGewebe" (transl.: Bullet Tissue) use a woven fibre system to position the foam spheres in space, see Fig 2 center.
For the "NetzGelege" (transl.: Non-Crimp Web) textile ropes form a network and so can absorb tensile and compressive forces, while foam was thought to serve as a connecting element and spacer between individual layers, see also Fig 7. The final project combined "Knit Foam" with the "Non-Crimp Web", meshing several layers of pressure-resistant lightweight ropes to form a lightweight 65 kg experimental pavilion, winner of the "Stuttgarter Leichtbaupreis" 2014 and TechTex Award "Textile Structures for New Building" in the area of micro-architecture (Fig. 3).
In a next step foam filled spacer fabrics, which are more suitable for a building envelope than filled textile sleeves, were used instead. Load-bearing structures based on three principles were then developed for space-enclosing structures: a shell structure produced in accordance with Heinz Isler's principles, (Fig. 4) a folded structure with foamed folds (Fig. 5) and a modular dome structure made of folded spacer fabrics. The dome (Fig 8) uses the spacer fabric's structure to create a modular, lightweight and translucent dome. To make the dome, open, pyramidal modules made of 30 mm thick spacer warp-knitted fabrics were folded and upended, making them stable like a hat. The modules were then joined together by foaming predefined voids between them, similar to Fig. 5d. Joined together they form a dome, due to their conically tapering individual forms (Sigmund, 2015). Conclusions for 3dTEX follow in chapter 4.1.

FIG. 2 FabricFoam© exhibition FFin, 2014: left "MaschenSchaum" (transl.: Knit Foam) S. Acikgöz, M. Haas, Ü. Kabadayi, center "KugelGewebe" (transl.: Bullet Tissue) T. Kielbasinsky, A. Mönner, right "NetzGelege"(transl.: Non-Crimp Web) M. Brehm, C. Goy, © Tobias Etzer

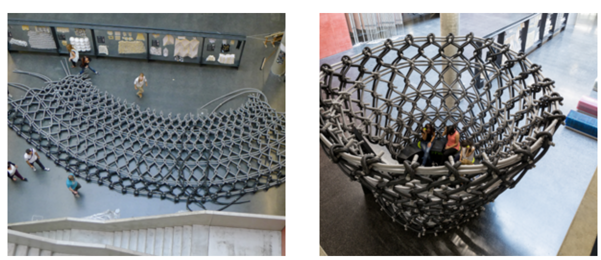

FIG. 3 Foamed fabric sleeves: Lightweight experimental pavilion FFin, © 3a FFin, © 3b Tobias Etzer.

FIG. 4 Shell structure, made of fully-fashioned foamed spacer fabric, FFin © 4a+b Christoph Lison, ©4c FFin.

FIG. 5 Fully-fashioned structure, folded foamed spacer fabric, FFin © 5a+b Christoph Lison, Fig 5c-d, Mock-up and detail, © FFin,

3.2 RESEARCH INTO TEXTILE-BASED LIGHTWEIGHT WALL STRUCTURES AND IN THE AREA OF TECHNICAL TEXTILES AND FOAMS

After an experimental start about potentials of foamed fabrics, research into comparable lightweight structures has been undertaken: Sandwich elements as well as rear-ventilated certified timber frame structures were chosen as a reference in terms of weight, dimensions and mechanical and building physics properties. Other similar products that could be project relevant, with comparable construction, stability and applications to the envisioned 3dTEX element, include KARODUR®, a fibre-based polypropylene hardboard used in combination with honeycomb or foam materials, and SAERfoam, made by SAERTEX®, which is a glass fibre-reinforced, closed-cell foam (PU/PE/PIR) for sandwich structures, whose strength and weight depend on the type of foam and on the density and direction of 3D glass bridges incorporated into it. Its fire safety properties can be optimised by adding a LEO Protection Layer (topcoat / gel coat). Another product of this type is Parabeam® 3d Glass, a spacer fabric and core material for sandwich structures made of glass fibres, that is stabilised by impregnating it with resin.

As a reference for 3dTEX were also researched experiments being conducted on spatial structures made of spacer fabrics at the ICD in Stuttgart and the research project “PaFaTherm II” at the TU Chemnitz. Here Professor Frank Helbig is working on foamed, textile-reinforced composite structural elements for automotive use. His latest findings were presented at the 15th Chemnitzer Textile Conference on 1.6.2016. The measurements of the foamed textile elements’ mechanical properties are promising. “With a fibre volume ratio of just 3%, clearly measurable effects that improved process and material performance were demonstrated” (Schäfer, Valentin, Meier, Roth, & Helbig 2014). Further research and development in Chemnitz will focus on multi-material design studies. E.g. OLU-Preg®-Organoblech (a multiaxial, textile-reinforced, thermoplastic fibre-plastic composite), polyurethane foam cores and 3D-knitted structure core reinforcement has been made into sandwich structures. Here too, standard bending and pressure tests showed absolute and specific performance improvements with different composite construction. (Schäfer, Jentzsch, & Helbig 2016) (Trölitzsch, Mehrkens, Loypetch, Helbig, & Kroll 2016). Conclusions for 3dTEX follow in chapter 4.2.

Apart from that an enormous range of developments is emerging alone in the area of technical textiles, which could expand the functionalities of a textile based façade element like 3dTEX in future. These include a thermal collector from spacer fabric developed at ITV Denkendorf, a fog collector textile, that captures water precipitated from fog and mist and also light-deflecting, luminescent, sensor-fitted, temperature amplitude damping and solar power producing textiles, that could make 3dTEX even more capable in future.

Other research projects only on foams in the context of 3dTEX are being carried out at the MIT Media Lab, Boston, where the "Mediated Matter" research group is working on foam structures that can define and enclose space. Researchers fitted a robot arm with a foam duct that can precisely distribute foam in space with the help of a computer, which could be a technique helpful for 3dTEX. Textile joining principles for use in prefabricated, customised building envelopes were also researched for 3dTEX, among them interesting products such as zip fasteners for corners, which the Renson company uses for its Panovista Max® product. Results from research carried out at the TU Graz on "facade4zeroWaste" using velcro fasteners to attach exterior weatherproof shells to insulating materials, allowing for easy installation and dismantling for recycling, also look promising e.g. in terms of possible connections between the 3dTEX elements. Conclusions for 3dTEX follow in chapter 4.2.

3.3 SELECTING TEXTILE TECHNOLOGIES SUITABLE FOR 3DTEX

Textile manufacture is still based on traditional principles such as braiding, knitting, weaving etc.. The spacer fabrics for the planned exterior wall elements, which are prefabricated, industrially produced (woven or knitted), with surfaces that are interconnected by pile threads at a specific distance and density, are very well adapted for filling because of the programmable cavities between the surface layers. As the goal is to use the surface layers as lost formwork, research has been necessary into appropriate textile technologies.

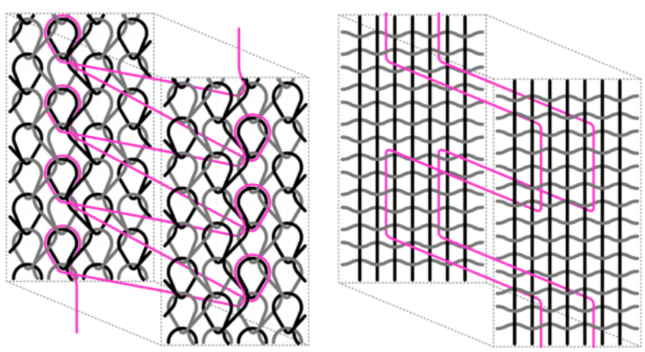

FIG. 6 Principle of knitted (left) and woven (right) spacer fabrics, © Graphic FFin.

Spacer warp-knitted fabrics are meshed, double-layered textiles. Their mesh structure makes them elastic in all directions, but additional weft and filler threads can also precisely restrict their elasticity. Their surface layers can be kept open and transparent. (Fig. 6 left). Woven spacer fabrics, in contrast, are double-layered woven textiles (Fig. 6 right). The linear structure of the warp and weft threads makes this material much less elastic than knitted spacer fabrics and dimensionally more stable. Unlike knitted spacer fabric, it can be used to make multi-layered and curved structures (Bauder, Wolfrum & Gresser 2015) with denser, closed surface layers that are less transparent. Conclusions for 3dTEX follow in chapter 4.3.

3.4 CONSTRUCTION OF FIRST DEMONSTRATORS

In order to find out about possible textile geometries and foam filling methods, for the beginning knitted and woven spacer fabrics have been used to make analogue demonstrators. Conclusions for 3dTEX follow in chapter 4.3.

Geometric and technical processing issues Spacer warp-knitted fabrics like those in mattress covers or seat padding were used for the first foamed spacer fabrics test elements. They were filled with commercially available PU foams. Research was carried out into the following issues:

- How does the foam behave in relation to the spacing pile threads, e.g. how does it spread in the cavities, to what extend and up to what density do the pile threads function as a barrier and "guardrail", and how do the spacer fabrics deform, depending on the width/height/depth of the cavities formed?
- How can the foam be precisely applied, e.g. to what extent are point-by-point, linear or planar foam filling methods appropriate for a specific textile geometry?
- How can the foam be precisely condensed through the pile threads (see results of PaFaTherm II) to optimise and include load-bearing functions in the 3dTEX elements while foaming?
- How can the design of the spacer fabrics be altered, so that variously dense and variously high areas alternate, with the goal of using higher areas for load-bearing and the flatter parts for insulating areas between them, while also achieving balanced U-values?

Production of project-specific spacer fabrics The next step was to produce project-specific spacer fabrics with channels free of the pile threads, intersecting in the fabric, that can be filled with foam and form a kind of support structure (post and beam system).They were made as both warp-knitted and woven spacer fabrics. Also three-layer woven spacer fabrics were produced. These three-layer (two-ply) woven spacer fabric have been first made as a mock-up. They had one layer with load bearing and insulating functions while the other spacer fabric layer with denser pile threads enables ventilation and protects the structure against moisture penetration and UV-light (Fig. 14-17). All the textile elements were filled with commercially available construction foams.

Measurements Parallel to the design of project-specific textiles three commercially available single-ply spacer warp-knitted fabrics were filled with different insulating foams to document qualitative differences between them and reference sandwich panel (see paragraph 4.4).

3.5 MATERIALS RESEARCH INTO FIBROUS AND FOAM MATERIALS

To generate a starting point for optimised fibre-foam combinations, tables of different groups of materials, with characteristics relevant to 3dTEX, were created for the textile technologies and for foams. In textile technology, a distinction is traditionally made between two main groups of textile fibres: natural and chemical fibres. To help the researchers compare textile with foams in the context of 3dTEX, textile materials were instead divided into organic and inorganic fibres. The fibres and foams were then divided into inorganic natural and inorganic synthetic, and organic natural and inorganic synthetic materials groups, so that they could be combined into similarly recyclable groups of materials in the long term. Around 40 different fibres and 30 foams were listed in tables and evaluated.

4 RESULTS

According to the research aims listed in chapter 3.1 to 3.5 the following results have been achieved:

4.1 RESULTS: EXPERIMENTAL PAVILIONS AND MICRO SPATIAL STRUCTURES

The first pavilion (built of pressure-resistant lightweight ropes (Fig. 3a-b), the second experimental dome-like pavilion (made of spacer fabrics, Fig. 8a-e, Fig. 21) and the micro spatial structures (Fig. 4a-c, Fig. 5a-d) demonstrate the specific textile design options of FabricFoam©. They also show the structural and lightweight potential of the individual structures and their specific integrated joining options.

For the first pavilion made of "pressure resistant lightweight ropes" for example, originally integrated joints were developed. Ramifying sleeving sections can be manufactured as an integral part of knitted and braided fabrics, as can specific openings similar to buttonholes. A semi-finished textile like this could be then adhered in one work process by making the nodes between the layers with foam, expanding through the buttonholes, see Fig. 7. The shell and folded structures also show the integrative potential of three-dimensional textiles. The shell is stabilised by an integrated foamed grid structure (Fig. 4b), while the folded cocoon structure has an integrated threedimensional beam structure (Fig. 5c). Here the spacer warp-knitted fabrics combine the functions of support structure and building envelope in one. Fig. 5d shows, how folded and foamed fabrics succeed in joining the surfaces through the foamed folds during folding, stabilising the structure and at the same time preventing potential thermal bridges in one work process. The experimental dome (Fig 8, Fig 21) combines the folding idea with a modular system and showed for the first time good mechanical properties as well as spacial qualities of the lightweight system form FabricFoam©. Negative results in this phase of the research project were the deformation of the PU-foam under loading and its UV-sensibility.

FIG. 7 Fully-fashioned, multi-layer structure consisting of pressure-resistant lightweight ropes made of foamed textile sleeves , © FFin.

4.2 RESULTS: RESEARCH INTO TEXTILE-BASED LIGHTWEIGHT WALL STRUCTURES AND RESEARCH RESULTS FROM THE AREAS OF TECHNICAL TEXTILES AND FOAMS

The product research yielded various interesting aspects for FabricFoam©, especially in terms of fire safety properties, such as the coatings SAERTEX uses. Among the important findings from the research are the many potential extra functions of technical textiles described above and the research results from the PaFaTherm II project in Chemnitz (see 3.2). Although Chemnitz focuses on applications for foams used primarily in moulded parts and for the car and vehicle sector, which has different mechanical and physical requirements, mechanical values and the results from research into the behaviour of foams and fibres are significant. Chemnitz found out that adhesion between foam and fibres is weakest for the combination of PE fibres and PU foam and strongest between PET fibres and PU foams, while the combination of PU foam and polyamide or glass fibres is in the middle range. The foam's porosity also changes near pile threads. The fibres partly destroy the foam pores and the foam condenses, which will be an important issue for 3dTEX as a potential gradient material with zones shifting from loadbearing to insulating areas.

4.3 RESULTS: SELECTION OF SUITABLE TEXTILE TECHNOLOGIES FOR 3DTEX

Warp-knitted and woven spacer fabrics each have advantages and disadvantages. For 3dTEX, specific versions of wall elements are currently being developed that are each based on either one or the other textile process. Research is continuing into elastic warp-knitted spacer fabrics for more plastically deformed facade elements. More rigid woven spacer fabrics with rather closed cover layers rather fit for planar facade components. Parallel it has to be taken into consideration, that the radii of the curvature of threads used to form mesh structures like knits make them generally less effective under tensile loads than woven textiles - while in woven spacer fabrics, the problem of the curved radii is reduced to the area where the pile threads are threaded into the cover layer.

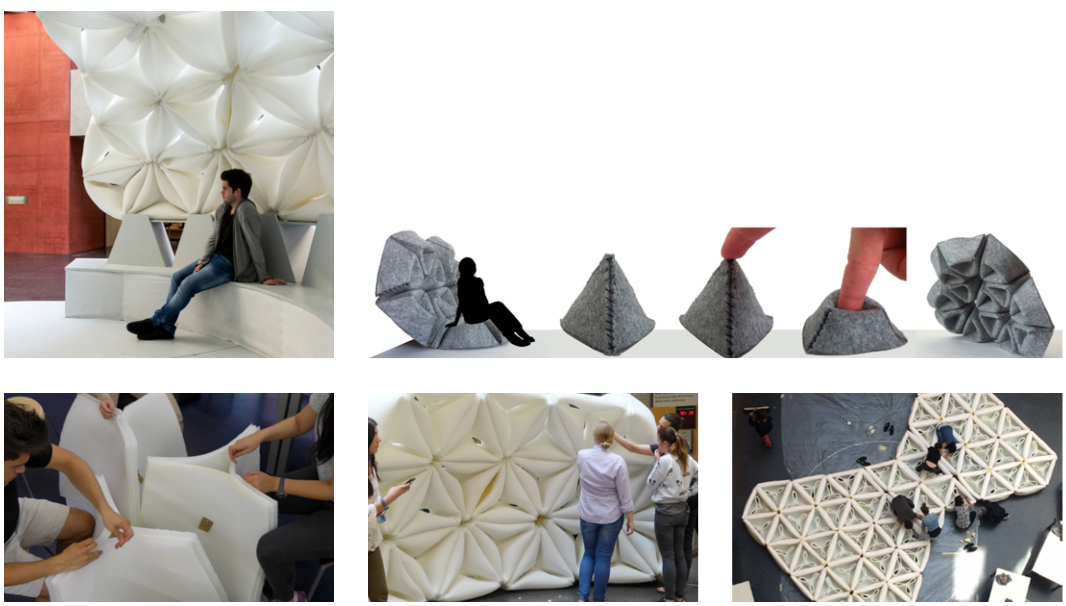

FIG. 8 Experimental pavilion: Modular system made of folded, foamed spacer fabric elements, © FFin.

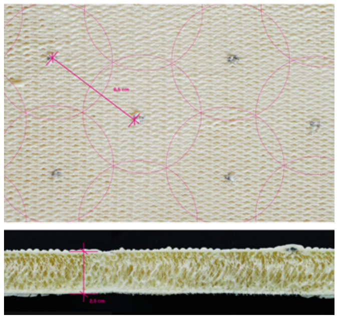

FIG. 9 Point-by-point foam filling of a commercially available warp-knitted spacer fabric, © FFin.

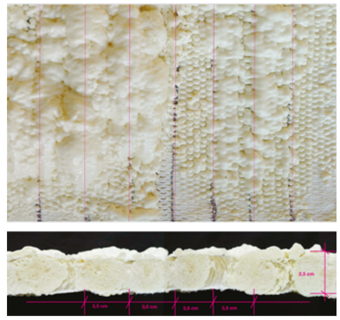

FIG. 10 Linear foam process of a linear thinned warp-knitted spacer fabric, © FFin.

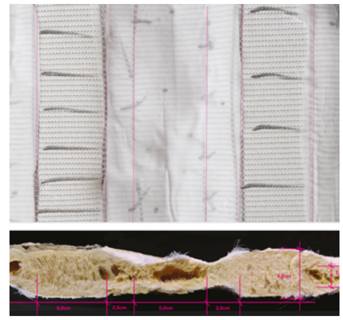

FIG. 11 Linear foam filling of a spacer fabric with variously dense pile threads in areas of varying heights, © FFin.

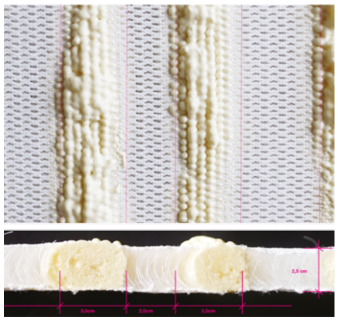

FIG. 12 Foam expansion and barrier effect of pile threads, © FFin.

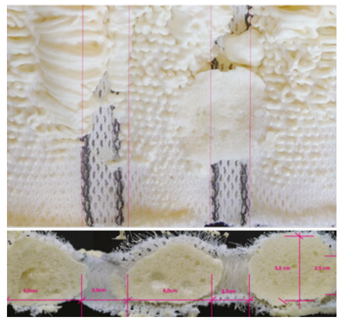

FIG. 13 Textile's deformation behaviour, © FFin.

4.4 RESULTS: CONSTRUCTION OF THE FIRST DEMONSTRATORS

Geometry and processing techniques The results of the tests shown in Fig. 9 to Fig. 13 show that the textile, in contrast to PaFaTherm, can be used as lost formwork if the number of pile threads in foam filled areas is reduced. A commercially available spacer fabric (see Fig. 9) with a high density of pile threads can only be completely foamed with the help of formwork and the addition of foam injections at various points. But in the test shown in Fig. 10 etc. formwork could be dispensed and planar foam filling be achieved, although it also showed that depending on the foam's pressure, it may permeate the porous mesh cover layer. This may be positive for the purposes of sealing or additional lamination of cover layers but would be negative in the context of UV resistance. Figure 11 shows an attempt to achieve a denser foam by modifying the density of pile threads in the higher areas of a warp-knitted spacer fabric. In the flatter areas, in contrast, the pile threads were eliminated and cover layers closed in the expectation that areas of foam with higher porosity and insulating effect would result here.
In terms of foam density, this result was partly demonstrated at the microscopic level, although it is evident that closed cover layers prevented PU foam from proper foaming in interstitial areas. Figures 12 and 13 show how cover layers, pile threads and foam mutually influence form and expansion behaviour, causing increased plastic deformations in pile thread-free channels.

Production of project-specific spacer fabrics The project-specific spacer fabrics produced in the next step have industrially prefabricated, pile thread-free, intersecting channel structures in a warp-knitted and a woven spacer fabric. It showed, that the different degrees of elasticity of the two textile types clearly produce two types of different deformation (see Fig. 14+15). While the warp-knitted spacer fabric perfectly adjusts and bulges in the intersected area, as occurs in pneumatic structures, the woven spacer fabric clearly shows wrinkling. Two different woven spacer fabrics were also produced, joined and filled with foam. By this two versions of a rear-ventilated structural element made of two-ply woven spacer fabrics were envisioned (Rear-Ventilated-Sandwich, ReVeSa, Fig. 16+17). They are under production and will demonstrate a complex textile geometry, fully fashioned.

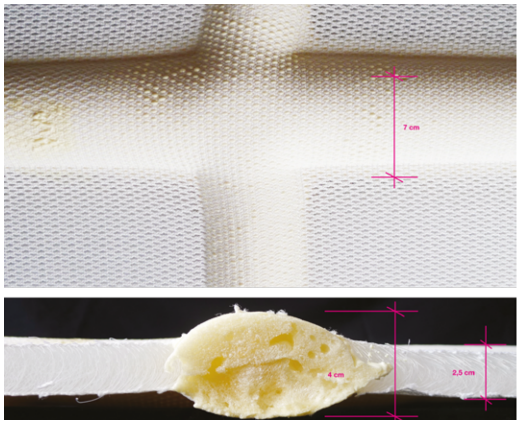

FIG. 14 Warp-knitted spacer fabric with foam channels, © FFin.

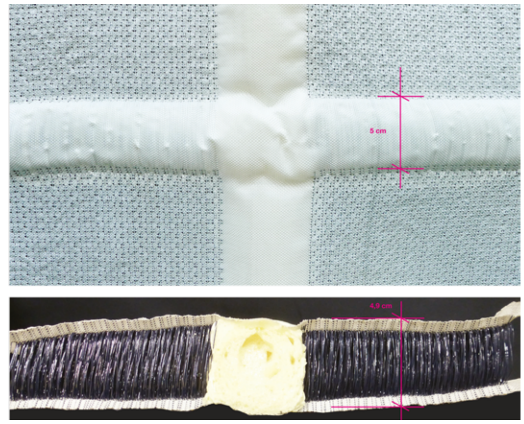

FIG. 15 Woven spacer fabric with foam channels, © FFin.

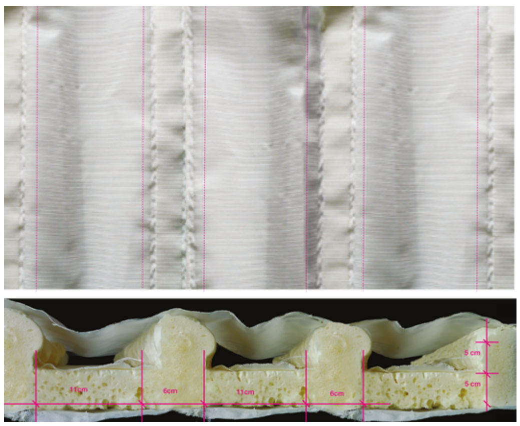

FIG. 16 Multi-layer woven spacer fabric, rear-ventilated sandwich, © FFin.

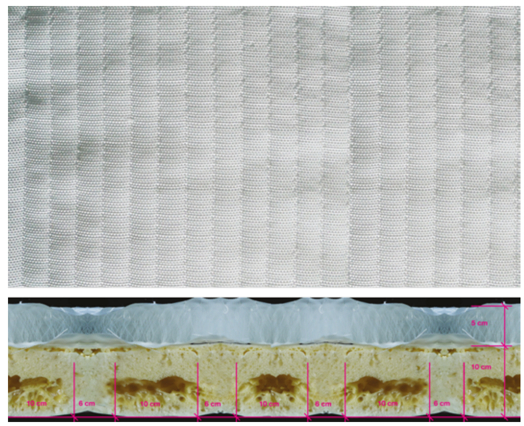

FIG. 17 Multi-layer woven spacer fabric rear-ventilated , alternative, © FFin.

Measurements of first demonstrators In the first test measurement, an identical 25 mm-thick polyester warp-knitted spacer fabric was measured without foam and foam filled with 2-component PU foam, with self-expanding 1-component rigid polyurethane foam and with isocyanate-free SMX foam. The measurements were made based on currently valid DIN EN standards and can be qualitatively assessed. **Bulk density:** The bulk density of the foam and of the textile differs from the bulk density resulting from adding the two to create a foamed textile, so the textile evidently causes the foam to condense during the manufacturing process. **Water absorption:** A precise statement on water absorption is not yet really possible because the test was not set up under constant climatic conditions and the handmade samples were not homogeneous. What is evident is that the composite of polyester fibres, with their very low moisture absorption, and foams, exhibited a higher water absorption than the figures for the foam alone. **Thermal conductivity value**: The thermal conductivity value of purely knitted spacer fabric was for the first time measured. The initial value provisionally arrived at was λ =0.035 W/mK, this seems too positive and needs to be checked again. As expected, the textile's thermal conductivity improves when it is combined with the tested foams and averaged out between that of the textile and that of the foam used, with values ranging from 0.023 to 0.029 W/mK. **Compressive and tensile stress:** Measurements of compressive and tensile stress in the longitudinal axis of the composite textile and foam samples show improvements compared with the purely foam sheet, which was expected after the measurements in Chemnitz. The first tensile stress values for foam were between 0.05-0.1 N/mm^2 and compressive stress 0.1-0.25 N/mm^2. Foamed textiles showed comparative figures for tensile stress of 0.6-0.9 N/mm^2 and compressive stress of 0.4-0.6 N/mm^2. **Gradient Material** Microscope analysis also proved, that condensation of a foam through the pile threads can be used to precisely and gradually increase compressive strength in specific areas.

4.5 RESULTS: MATERIALS RESEARCH INTO FIBROUS AND FOAM MATERIALS

In the current experiments as described above polyester fibre textiles were combined with PU–based foams. Based on the materials tables made during the research, initial conclusions can now be drawn. (Fig. 18-20). The statements below refer first to the fundamental applicability of individual groups of materials, then to their typical tensile and compressive strengths and thermal conductivity values. Finally the fibres' UV-resistance and flammability classifications were also examined, as the textiles function as a lost formwork for 3dTEX.

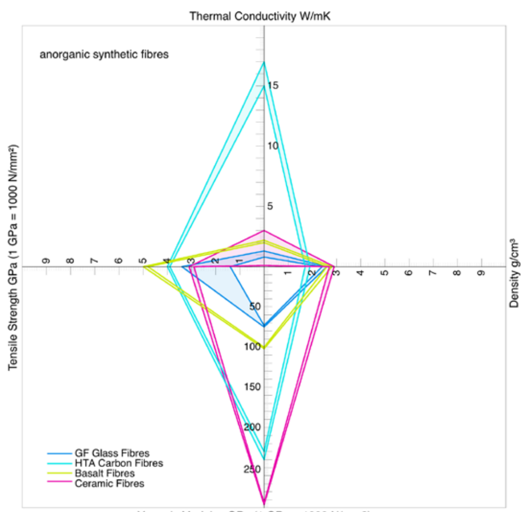

FIG. 18 Comparison of glass, carbon, ceramic and basalt fibres, © FFin.

Fibres Almost all fibrous materials can be used as spacer fabrics, although brittle materials, such as glass fibres may be an exception in the area of pile threads depending on the mesh radius / material thickness / connecting loop radius, because these subject to greater bending in the area of the cover layers which causes them to break. The textile will be used as lost formwork, so one essential criterion is UV resistance. Organic fibres are less effective here, although synthetic organic fibres can be optimised with additives. In contrast, synthetic inorganic fibrous materials are UV-resistant and not flammable (glass, basalt carbon fibres like PANOX®, or ceramic fibres). In terms of other properties, Fig. 18 shows which inorganic fibre materials have a potentially higher tensile strength as well as lower thermal conductivity. Here, carbon fibres are less effective than ceramic, glass or basalt fibres. Taking the modulus of elasticity into account, basalt and ceramic fibres remain an interesting prospect.

Foams In the context of 3dTEX, a distinction must be made between foam insulating materials used in construction and structural core materials for lightweight structures in vehicle and ship building, wind power turbines etc.. The latter are interesting in the context of 3dTEX because they have much better mechanical characteristics than insulating materials yet also good insulating properties (Fig. 19). The selection criterion of UV resistance (see fibres) only plays a role for 3dTEX for foams in combination with warp-knitted spacer fabrics and their open-pored cover layers, otherwise the results would be the same as for the fibres. Additives can make synthetic organic foams UV-resistant, and adding them to PU foams can enable the foams to attain at least a B1 flammability classification. In terms of fire behaviour, inorganic materials, such as foam glass or foam concrete, are more suitable here. In an overall comparison, see Fig. 20, it is evident that PMI foams such as Rohacell, with their wide range of applications, can achieve greater strengths than foam glass, for example. They cannot achieve the mechanical values of solid construction timber but can compensate for that with much less density due to their relative very high strengths. A further criterion in selecting project-relevant foams is the issue of closed-cell or open-cell foams. Closed-cell foams could be used in a single-layer warp-knitted spacer fabric building envelope, while this requirement could be dispensed with in multi-layer, rear-ventilated woven spacer fabric structures (e.g. Fig. 16+17). Various technical questions concerning processing are currently under research, such as which foam production process (physical, chemical, mechanical or syntactic) is best suited to foaming which textile geometry.

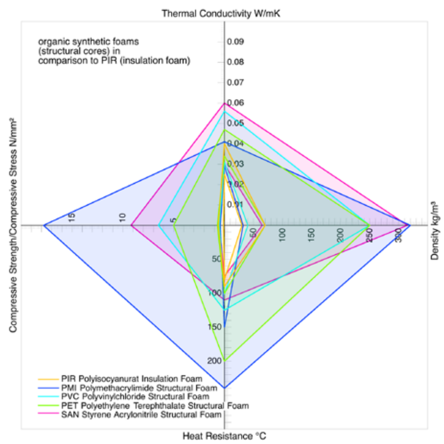

FIG. 19 Comparison of construction core materials compared with PIR thermal insulating materials, © FFin.

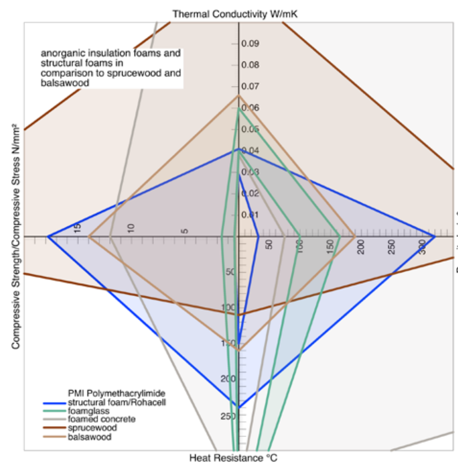

FIG. 20 Comparison of organic and inorganic construction core materials with timber, © FFin.

Fibres and foams Overall, several initial tendencies can be identified. The ongoing 3dTEX research project will need to achieve high mechanical and insulating values with a low density, UV resistance for at least the cover layer, and the highest possible flammability classification. Here, the inorganic materials groups have considerable advantages, although the issue of weight is only dealt with in combination with high-performance materials such as PMI foams. If integrative products are to be manufactured, the production of a fully fashioned manufactured textile will be as important as foam filling. Here too, current findings show that e.g. PMI foams could be interesting because they can be foamed as granulate at temperatures ranging from 170 up to 210 degrees.

5 CONCLUSIONS

The two pavilions and the two smaller spacial structures were experimental approaches towards lightweight constructions. They showed the potential mechanical properties of foamed fabrics (FabricFoam©), due to synergies between textile and foam structures. The foamed sleeves from the first pavilion can divert tension as well as compression forces, while the weight of the whole construction is only 65 kg. Also the dome from folded spacer fabrics relies on the combination of fibres and volume based materials: The foamed parts between the modules absorb compression forces, while the fabric fibres absorb tension forces. The next tests with spacer fabrics showed, that adopting classical loadbearing structures as folding techniques and shell structures helped to further reduce the amount of fabric needed. By this the weight could be reduced in comparison to the opulent dome structure. On top, especially the shell structure showed, how prefabricated textile cavities allow a perfect integration of the foamed materials in the spacer fabric. The spacer fabric textile acts as a lost formwork, the foam fills the cavities, and together they become a complex threedimensional integrative loadbearing structure. In contrast to conventional steel and textile structures, that needs additive manufacturing, here an integrative "fully-fashioned" structure appears with additional architectural qualities, so as light transmission and sound absorbation.

Parallel to the experimental approach towards spacial structures, 3dTEX on one hand looked for a better understanding about the interaction of fibres and foams (see chapt. 4.4) and found out, the pile threads function perfectly as a barrier and "guardrail". The foam itself acts in a way lazy, meaning it fills every easy available space in the spacer fabric rather than penetrating though the surface layers – even if they are permeable. The deformation of the spacer fabrics is in a way is similar to pneumatique structures, but is depending on the chosen textile technology. The elastic warp-knitted spacer fabrics are better suited for more circular geometries, while the woven spacer fabrics fit better to linear structures. In terms of filling methods linear ones, similar to sandwich production technologies, where more efficient than point-by-point methods. In terms of mechanical properties especially interesting where microscope studies that confirmed results from Chemnitz and Prof. Helbig. The foam becomes condensed through the pile threads, which offers options towards gradient foamed spacer fabrics. First tests with areas of variously dense pole threads and variously high areas alternating showed gradient foam densities. Here research is ongoing, in order to find out how to precisely use this option for thicker, denser loadbearing areas varying with thinner, insulating areas, made from the same foamed material and still offering the same U-value.

On the other hand research went into optimisation of fibre and foam material combinations, so 3dTEX started looking for fibres with a high resistance against tension forces, foams with a high resistance against pressure forces, and foams and fabrics with a low thermal conductivity. As is shows (see chapt. 4.5), especially basalt fibres and PMI-foams as Rohacell match these expectations. In comparison, the latter finds itself between spruce wood and foamed concrete in terms of pressure forces but has lower thermal conductivity then both of them. Further research is needed here, among other things, into recycling aspects, but it shows, that the proposition is still valid.

Overall, the textile geometry of spacer fabrics has been looked into and has been further developed with the partners. A three layer woven spacer fabric, similar to the mock-up (see Fig. 18), has been developed and is in production in a "fully-fashioned" process at the moment. It will be foamed and tested as a ventilated two-ply wall element in the next step. Also a two-layer warp-knitted fabric is in production, similar to Fig 15, with the areas between the loadbearing structures now free from pole threads. Also this fabric will be foamed and tested then as a one-ply wall element in the next step. The work done by now shows, that the proposition of the "fully-fashioned" building envelope, made of a foamed spacer-fabric, is still valid. Further research is ongoing here at the moment in order to achieve the proposed lightweight, prefabricated elements, that meet in perfect combination structural, climatic and aesthetic demands, for new as for exisiting buildings and temporary shelters.

In the next research project the aim would then be to embedd research results from smart textiles like solar-thermal energy production, electric energy production by the use of semiconductor coated textile surfaces or fibres, the use of glasfibers for daylightcontrol and light deflection and the use of the textile surface itself for sound absorption.

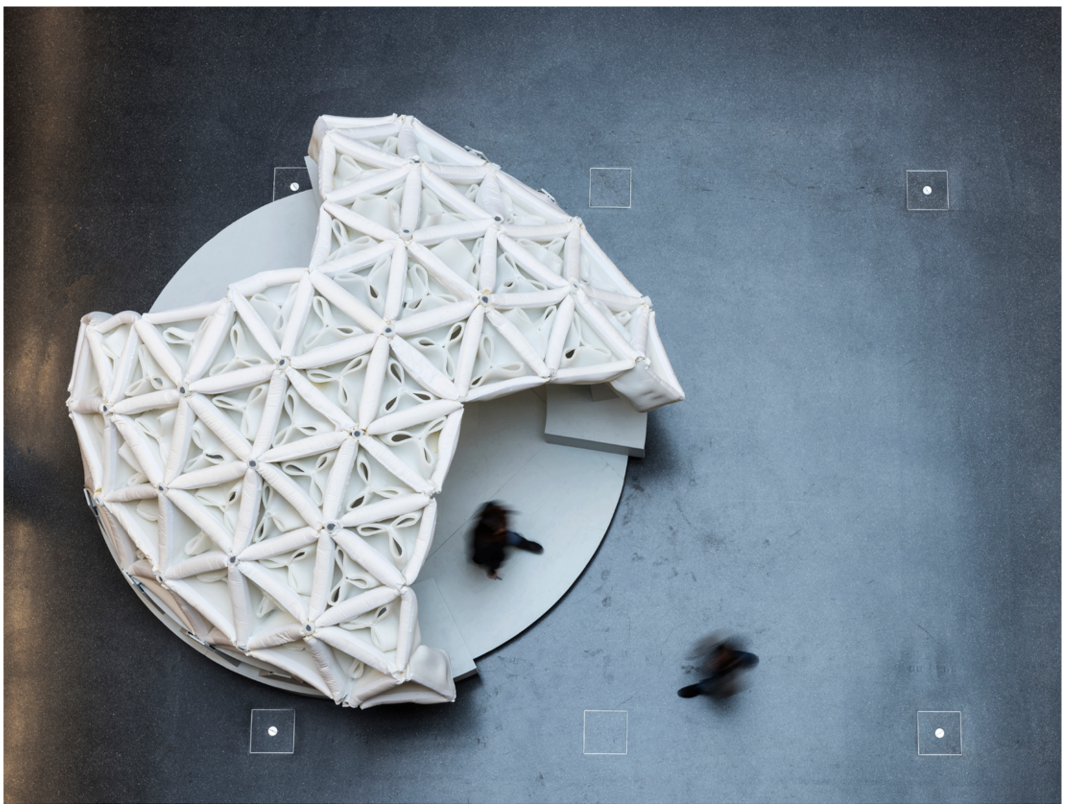

FIG. 21 Experimental pavilion: Spacer fabric modules, folded and foamed, FFin, (textile materials provided by Essedea GmbH & Co. KG), © Christoph Lison.

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