Microbiologically Activated Knitted Composites

Reimagining a column for the 21st century

Bastian Beyer[1], Daniel Suárez[2], Norbert Palz[3]
[1]Royal College of Art [2,3]Berlin University of the Arts
[1]bastian.beyer@rca.ac.uk [2,3]{d.suarezzamora|n.palz}@udk-berlin.de

A column is an archetypal constituent of architecture which historically underwent constant reiteration in accordance with the prevalent architectural style, material culture or technical and structural possibilities. The project reimagined this architectural element through harnessing the synergies of digital design, textile logic, and contemporary biotechnology. Textile materiality and aesthetic are deeply rooted in architectural history as a soft and ephemeral antipode to rigid building materials. An investigation in historic mechanical hand-knitting techniques allowed to extract their underlying structural and geometric logic to develop a structural optimisation pipeline with a graded yarn as a base material and a geometric optimization based on local distribution of knitting patterns. Bacterially driven biocalcification was applied to transform the soft textile structure into a rigid material. Hereby an active textile microbiome was established through colonizing of the yarn with the bacterium S. pasteurii which successively precipitated calcite on microscale within the textile substrate hence ultimately influencing the global structural behaviour of the column.

Keywords: *textile microbiome, material customization, knitting, yarn augmentation*

INTRODUCTION

The column 21 project emerged from a cross- European collaboration and an interdisciplinary exploration of the fields of textiles, biotechnology, material engineering, digital design, and architecture. The aims were to find unconventional solutions for novel material processing and innovative approaches towards sustainability through an exchange between design, engineering, and biotechnology.

The building sector is among the biggest contributors to our environmental impact and C02 emissions hence architects need to acknowledge the environmental impact their design decisions and material choices.

The project employs two strategies to increase its efficiency and sustainability. First, two structural optimization operations, consisting of an engineered graded yarn (saving approx. 28% material) and a topological optimization through local knitting pattern distribution based on a structural optimization analysis.

The second strategy consists of applying solely materials based on renewable resources and biological processes. The substrate material consists of natural jute which, in a second step, is treated with an active bacterial culture of S. pasteurii. This process generates a reactive microbiome on the textile substrate and triggers a microstructural transition through bacterially induced calcite precipitation.

The generated material renders a bio-derived textile-based composite generated through a biochemical process. Through the use of this biological activity as well as the renewable base material the material accounts for a much lower embodied energy balance than similar cementitious products.

Furthermore, the in-situ treatment allows a reduction of transportation effort. Therefore, the material presents a more sustainable alternative to conventional energy-intense and pollutive construction materials.

CONTEXT

The project investigates microbiological agency within knitted textile material systems for novel composite materials. Biological systems offer unique characteristics for reactive and adaptive building materials (Cruz and Beckett 2016). Recent developments within biotechnology, especially in the field of synthetic biology, induced a shift within contemporary biology, transforming the discipline from a mere observatory to a generative practice (Ellis et al. 2011; Luisi 2007). This paradigm shift offers the potential to not merely extracting resources from nature but generating new materials through nature. The application of biological systems within architecture and design demands an extensive consideration of substrate materials and scaffolds to bridge the scalar gap between nano and macro scale. Fibrous materials hereby offer a suitable medium for a designed textile microbiome allowing for a controlled spatial application of biological systems. The combination of fibrous substrate and microbiological agent results in a sui generis class of composite materials which utilises nature's inherent metabolism within a material system comprised of a bio-active matrix and a fibrous substrate.

Textile manufacturing methods hereby provide a superordinate geometry for the fibrous system. The interplay between the three main focal areas - fibres, geometry, and the distinct textile microbiome- equivalently contributed to the final outcome allowing for a novel composite material system. A textile microbiome is understood as a community of microorganisms inhabiting a specific fibrous substratum (Burge 1988, Mcqueen 2007, Callewaert 2014).

Fibrous materials offer a suitable medium for microbial colonisation, due to their increased surface area and moisture retention ability. The textile microbiomes are in constant (biological) exchange with their environment which varies in their activity depending on external and internal conditions as well as the specific strains of microorganisms on fibre level. Through the utilization of the property of textiles to "host" specific microbiomes and by designing a distinct tailored textile microbiome whose activity and reactiveness can be determined and controlled, novel bio-active and responsive composites emerge.

While the textile microbiome accounts for the reactivity of the material, the textile substrate presents the form-giving entity.

Knitted fabrics hereby offer an extremely versatile and adaptive textile platform which can be produced with wide-ranging properties depending on various parameters, such as fabric geometry, yarn material, and machine or hand dexterity thus defining the behaviour and performance of their resulting mechanical properties. This kind of fabrics can be fully programmed with differentiated material properties and heterogeneous compositions. Their ability to transform continuous raw material into three-dimensional shapes invites new synergies between knitting and emergent digital fabrication technologies (Steed 2016). They allow for an extensive range of applications within the architectural domain and to be utilized as a substrate material for a distinct microbiome.

Modern knitting technology benefited from advances in computer numerically controlled (CNC), new materials and knitting machine improvements. In comparison to woven fabrics, knitted material systems are extremely stretchable and conformable, making them convenient for e.g. composites preforms (Araujo et al. 2011; Padaki et al. 2006), to work embedded in other materials, or as in-situ formworks for concrete casting (Popescu et al. 2018).

Recent projects have also introduced knitting on an architectural scale for multi-performative hybrid structures (Ahlquist and Menges 2013; Tamke 2015) or in combination with pneumatic actuators for reinforced and programmed knitted structures (Baranovskaya et al. 2016). Knitectonics (Chaturvedi et al. 2011) also tackles the question of programmed material distribution - with differentiated properties - using domestic craft tools, such as small circular flat weft knitting devices, conveniently hacked to be computer numerically controlled.

These outlined projects explore the possibilities of knitting as a material construction method to achieve complex geometries, albeit, they only utilise yarn sizes that existing machines can process.

The following research proposes a different strategy to reach the architectural scale through the concept of yarn augmentation. This approach not only leads to an up-scale factor or an increased yarn diameter (> 5mm) but also facilitates an enhanced yarn functionality with amplified material capabilities allowing the transition of the structural system from tensile to compressive load-case. In contrast to a membranous textile system, the increased diameter of the augmented yarn provides sufficient bending-resistance and compressive strength to function as a space frame.

DESIGN TO FABRICATION

Preface

The project applies multiple design strategies located in different disciplines. Within this interdisciplinary and the (multi) methodological framework the project tried to locate disciplinary synergies and systemic overlaps. The presented demonstrator tried to frame this disciplinary connectivity through its distinct design-language.

The following chapters aim to elucidate the main methods applied throughout the project. Although the presented demonstrator wants to be understood as one integrated system, the following chapters will discuss the individual aspects separately.

Design objectives

The modular base structure (fig.1) served as the primary infrastructure and staged the fabrication processes, conceptually and physically concentrating the various research streams and disciplines. It can accommodate secondary modules for knitting (circular knitting device) and material treatment (bioreactor).

The knitted column was manufactured with one continuous textile material (referred to as substrate material in the following text) on the customised circular knitting device.

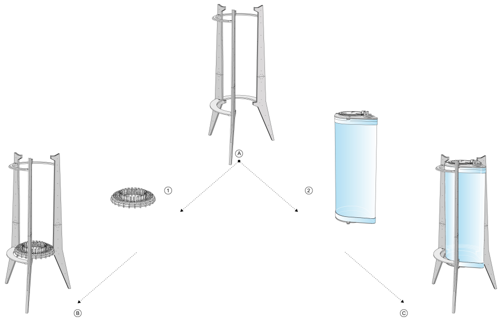


Figure 1
Custom modular base structure

Two structural optimisation strategies were applied within the structure:

1. Topological optimisation through a graded substrate material
2. Geometrical optimisation through local variation of knitting patterns

Successively, the finished knitted structure underwent a treatment in the Bioreactor which established an active textile microbiome on the substrate material.

Upon external stimuli, the microbiome triggered

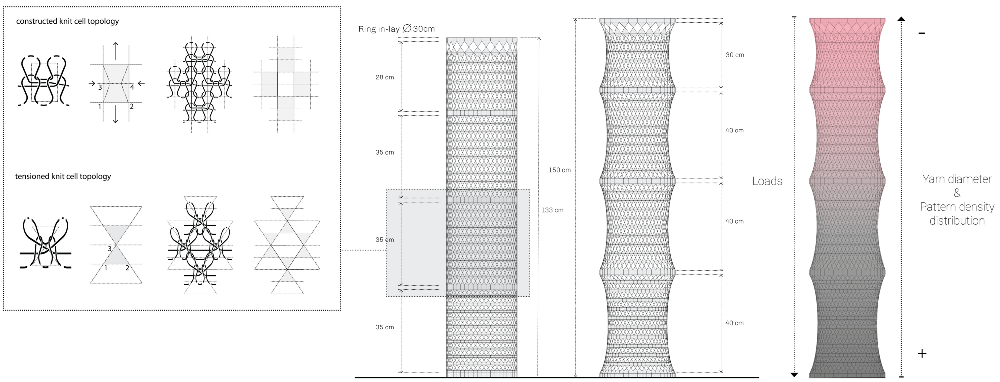


Figure 2
Design concept

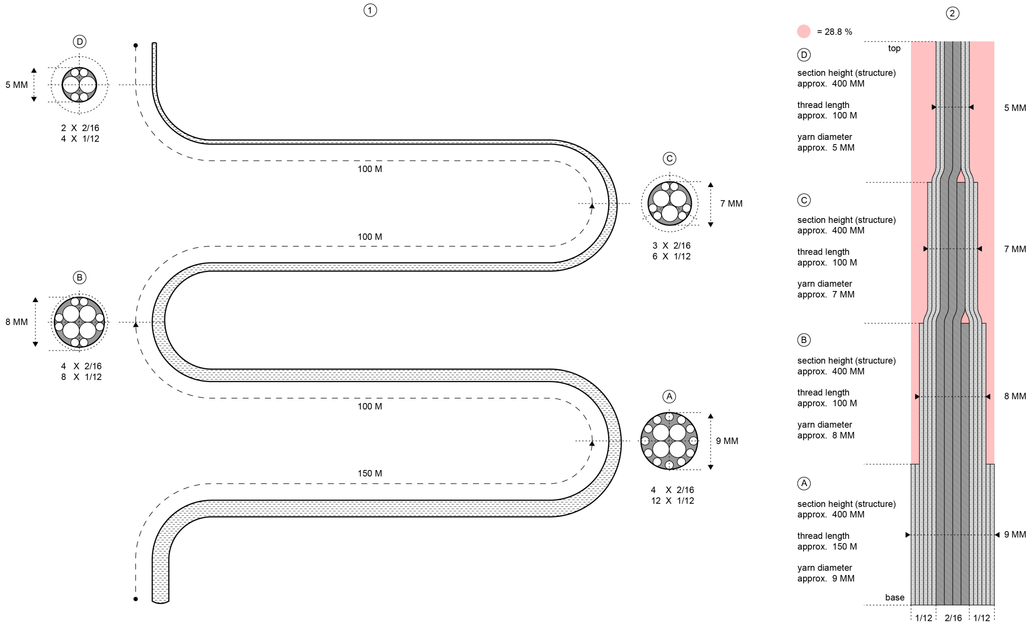


Figure 3
Graded yarn diameter and distribution

a bacterially induced calcification micro-level, gradually solidifying the substrate material and transforming the soft textile structure into a load-bearing composite.

Analogue and digital textile design process

Knitting offers a unique material manipulation technique. A constant manufacturing setup (loom) and technique (knitting) allow for a geometric manipulation (pattern) of a textile material system while maintaining its topology (yarn) as well as material continuity (yarn).

The project tried to harness this principle and combine it with digital design tools for an approach to geometric optimisation.

The design method applied in the project merges a digital approach in form of a parametric design process and traditional textile craft methods to establish a feedback loop between digital simulation and analogue fabrication.

The distinct local pattern variation within the textile structure was based on a form-finding process utilizing Rhino 3D and Grasshopper as a modelling platform to generate a parametric model of the column including the dimensional constraints of the setup.

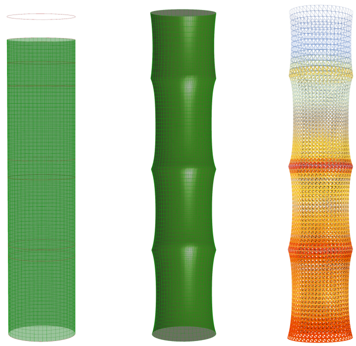


Figure 4
Frame analysis and material distribution

Hereby a 3D model of the anticipated column is modelled as a cylindrical mesh and re-topologized in correspondence to a selection of knitting patterns which allows to extract information for yarn material consumption as well as to explore form-finding methods. A physical simulation of the tensile textile system with Kangaroo allowed to extrapolate the final geometry. A further parametric structural analysis utilizing Karamba finite element modelling determined the weak points of the structure and provides insight to the local structural utilization of the system. The generated data enabled to determine the necessary diameters for material manu-facturing and pattern distribution.

The selection of the patterns was determined by the following parameters:

1. Tensed geometry: Figure 2 illustrates the Geometrical transformation while tensing. The selected patterns displayed, upon tensing, a transformation from orthogonal to diagonal logic. This effect was utilized to achieve a cross bracing effect.
2. Pattern density: specific knitting techniques can influence the density of a textile structure hence generating openings and permeability. This allows local material deposition only through the variation of knitting patterns
3. Pattern thickness: the knitting patterns can be influenced through specific knitting techniques which leads to a layering of the individual strands. The pattern thickness influences the transverse section of a knitted system hence influencing its structural behaviour.

Material customization - Graded yarn diameter

Knitting utilizes a continuous textile semi-finished material (such as yarn) to generate interlinked structure in the form of a textile. While the geometry of the semi-finished material changes fundamentally, its topology remains constant. Introducing a gradient within the continuous substrate material enables to control the material deposition within the structure on a topological level.

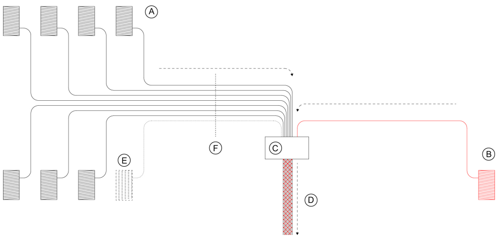


Figure 5
Hybrid yarn fabrication concept.

The main challenge for the substrate production was to find a fabrication process suitable to gradually reduce the diameter of the substrate from 9 mm to 5 mm while maintaining material continuity over the total length of 450 m.

The substrate material consisted of a multi-strand jute core with an external sheath (fig.5). Controlling the density of the sheath was found to be a crucial factor of the material design as it tremendously affected the knitability as well as the liquid permeability of the material for the bacterial treatment.

Therefore, the sheath needed to be dense enough to contain the fibre bundle while at the same time not restricting it's bending capacity as it would affect its knittability. Similarly, the sheath influences the permeability to liquid which is an important factor for the final bacterial treatment process.

The continuous substrate material in the context of this project is constituted of a multilayer structure that allows a variety of different material configurations.

Conceptually, our yarn is closer to current hybrid yarns with core-sheath structures. Hybrid yarns are engineered yarns, in which various materials are combined in one strand to create different structures based on the performance requirements of the final product. (Alagirusamy et al. 2006; Mankodi 2011). Over the last years, various means of producing technical cord-like hybrid yarns have been introduced for the development of innovative applications. Solutions range from KEMAFIL® (KEM) technology for manufacturing rope-like structures of diameter 4-27mm for novel geotextiles (Arnold et al. 1994; Broda et al. 2017) to narrow circular knitting machines to knit around a core which is used for the production of flexible e-yarn of diameter 2 mm with inclusion of electronics (Hardy et al. 2019). Although this last fabrication technique was tested in the context of this research however it produced a denser sheath than it was desired.

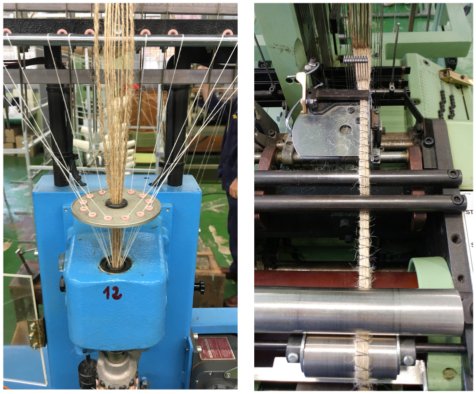


Figure 6
Hybrid yarn fabrication process. Narrow warp knitting around a core (left). Narrow weaving ribbon (right).

Finally, the method adopted in the context of the presented project allowed for a customized weaving process which bundles the multiple strands of jute twine to generate the desired diameter whilst keeping control over the sheath stitch density. At the same time, the process allows subtracting individual strands during the production process hence allowing for a locally graded materiality with variable diameter.

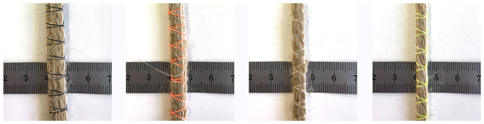
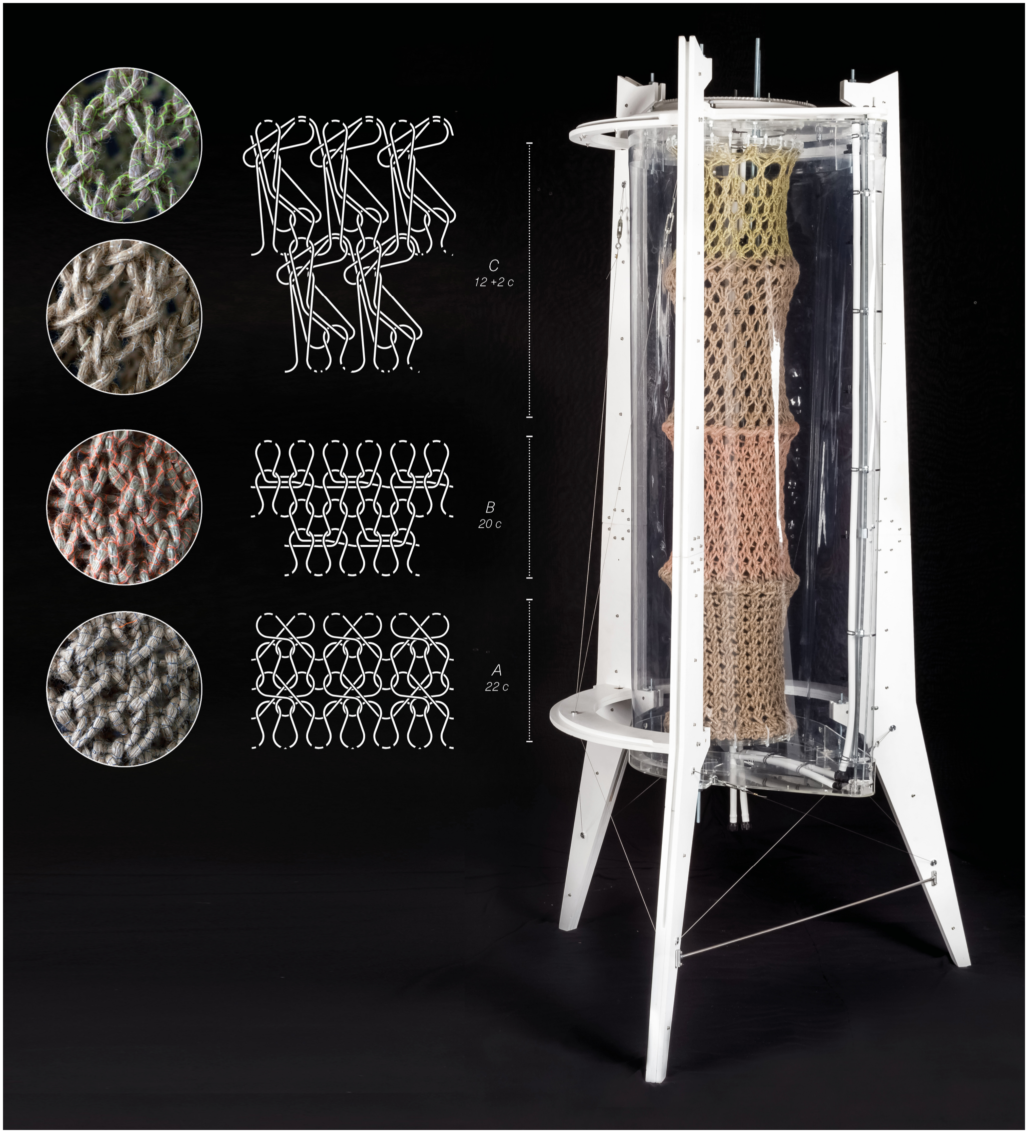


Figure 7
Graded yarn diameter

This material gradient throughout the continuous substrate material allowed to reduce material consumption by 28%.

Figure 8
Finished soft knitted column inside the bioreactor and pattern distribution



Material organization - Graded pattern density

Conventional industrial knitting machines are not designed to knit extremely coarse or heterogeneous yarns thus calling for a manual manufacturing process. Therefore, the project employs the more suitable and less yarn- dependent manual fabrication processes for prototyping purposes. Opposed to textile machinery which is generally product-oriented and bound to a limited material palette suitable for each technology, handcrafting techniques open up possibilities for alternative purposes and non-conventional materials (McQuaid 2009).

Although manual craft techniques are more time consuming compared to automated processes and demand a high level of dexterity, they allow for more complex patterns and structures which are not possible to manufacture with industrial machines. Therefore, they are ideal for manipulating and prototyping with non-uniform and graded yarns.

The technique employed during the project is inspired by historical textile craft methods, namely peg frame knitting which is a widely applied technique in domestic hand knitting devices. Some scholars pointed to this technique to be more likely the model for William Lee´s 1589 first knitting machine - the stocking frame (Hills 1989).

This specific craft technique is an accessible alternative to conventional hand and industrial needle knitting as it uses a frame with pegs and a hook tool instead of needles to form the stitches on each peg.

This knitting device can be understood as a fabrication process situated between hand knitting and flat weft-knitting machines. An extensive pre-study generated a taxonomy of diverse knitting patterns suited for the customized loom as well as the material. A categorization of the knitting patterns was established in accordance to their density, geometry, direction and material consumption. The application of selected knitting patterns was then realized through the manual manufacturing process.

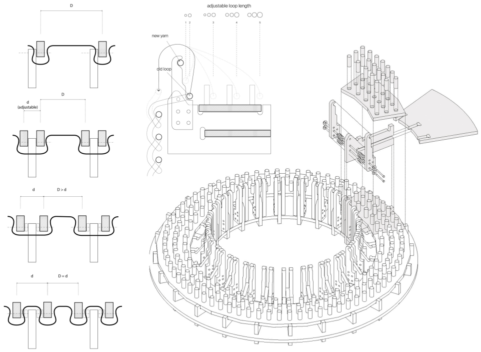


Figure 9
Tailored circular hand knitting frame with variable gauge and adjustablöe loop length features

Material activation - Graded bacteria deposition

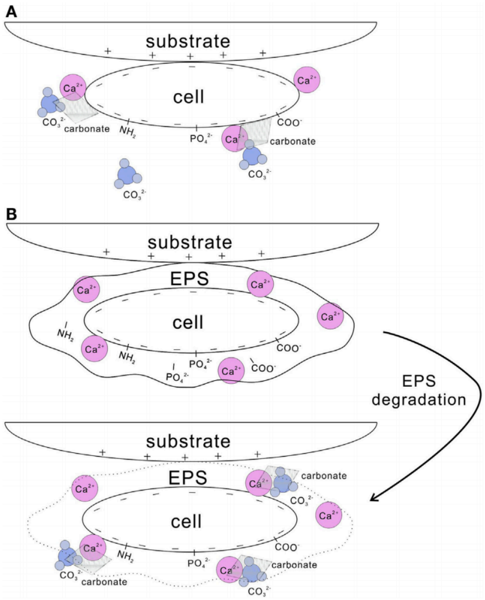
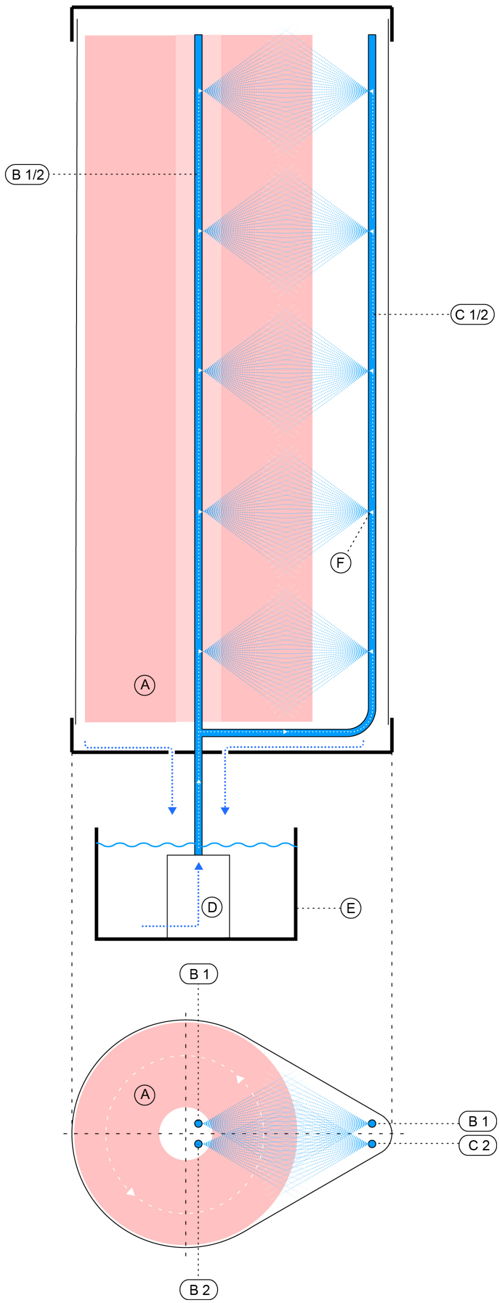


Figure 10
Active textile micro-biome

After the manual knitting process, the loom module was exchanged with the bioreactor module for the final treatment process. Through a controlled irrigation process within the Bioreactor, an active S.

Figure 11
Bioreactor functional diagram



pasteurii bacterial culture was applied to the textile structure. During this treatment, the bacteria adhered to the microstructure of the jute fibres, gradually establishing a distinct textile microbiome.

In nature, this biochemical reaction is abundantly occurring in soils, sand or maritime microbial mats. In these cases, the precipitated calcite gradually solidifies the granular media through microscopic calcite links binding the individual grains together (Dupraz et al. 2009; Esnault Filet et al. 2012).

The project's aim was to investigate this process on a fibrous jute substrate in order to establish a bacterially derived calcite matrix hence influencing the global structural behaviour.

The treatment was based on the Biocalcis protocol (Esnault Filet et al. 2012) which is designed for large scale sub terrain grouting applications for granular media. For the project, a novel rotational irrigation system to deposit the bacterial culture was designed (fig) to adapt the process to the design objectives.

After the textile structure developed its distinct microbiome a secondary treatment with urea and calcium chloride was applied which triggered the calcification process. Over a timeframe of three days, the treatment was repeated eight times with each round increasing the calcite deposition on micro level hence consolidating the textile structure.

CONCLUSION

The project operates between and utilizes the inherently different domains of binary and biological computation. Conventional binary computation enabled a digital parametric form finding process based on empirical experimental data and intrinsic material properties. The material biological transformation, however, is initiated by a living organism hence follows a different information system. As all living beings, its means of information processing and replication follows the regime of chemical DNA "software".

Working with living, active organisms opposed to conventional non-living materials offers a new perspective on materiality. Living systems, by nature, display active, reactive and responsive behaviour and stand in constant exchange with their environment through their natural metabolism. Bio-active materials can harness their unique and intrinsic co-creating agency and inherent biological complexity.

Figure 12
Textile bio-solidification composite process.Macro, meso and micro scale

The incorporation of biological agency within material systems furthermore offers to potentially harness intrinsic biological characteristics such as self-healing or self-generating structures as well as adaptive and responsive properties based on biological metabolism. In contrast to electronic or mechanic means of actuation, these biological systems operate on micro and nano-level and draw their energy directly from their environment through metabolic processes. The project exemplifies that for innovation to happen we must abandon our disciplinary boundaries and foster an active knowledge exchange.The project established a novel multi-actor design process encompassing the fluid interaction of human craftsmanship, digital fabrication and computational analysis and simulation as well as biological formation processes to generate a multi-hierarchical material system resulting in a unique architectural artefact

ACKNOWLEDGMENT

We would like to thank Annette Esnault Filet (Soletanche Bachy) and the Biocalcis Team who contributed to the Project extensively with their knowledge and experience in the field of bio-calcification and providing the bacteria for the tests. As well as Brice Desvages (Soletanche Bachy) who was great support supervising the biochemical processes on site. Also to the people of the textile research center EURECAT in Canet de Mar, Spain for competent consulting in regards to textile technology as well as facilitating the fabrication process. Last, thanks to Albert Palen for the photography of the final installation.

This project has received funding from the European Union'sHorizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 642328.

REFERENCES

Ahlquist, S and Menges, A 2013 'Frameworks for Computational Design of Textile Micro-Architectures and Material Behavior in Forming Complex Force-Active Structures', *ADAPTIVE ARCHITECTURE*

Alagirusamy, R, Fangueiro, R, Ogale, V and Padaki, N 2006, 'Hybrid Yarns and Textile Preforming for Thermoplastic Composites', *Textile Progress*, 38(4), pp. 1-71

Araujo, MD, Fangueiro, R and Hu, H 2011, 'Weft-knitted structures for industrial applications', in Au, KF (eds) 2011, *Advances in Knitting Technology*, Woodhead Publishing, pp. 136-170

Arnold, R, Bartl, AM and Hufnagl, E 1994, 'Production of cord and narrow fabric products with Kemafil technology', *Band und Flechtindustrie*, 31, pp. 48-52

Baranovskaya, Y, Prado, M, Dörstelmann, M and Menges, A 2016 'Knitflatable Architecture: Pneumatically Ac-

Figure 13
Self-supporting bio-calcified composite knitted column. Result after treatment

tivated Preprogrammed Knitted Textiles', *Proceedings of eCAADe 2016*, p. 10
Broda, J, Gawlowski, A, Laszczak, R, Mitka, A, Przybylo, S, Grzybowska-Pietras, J and Rom, M 2017, 'Application of innovative meandrically arranged geotextiles for the protection of drainage ditches in the clay ground', *Geotextiles and Geomembranes*, 45(1), pp. 45-53
Callewaert, C, De Maeseneire, E, Kerckhof, FM, Verliefde, A, Van de Wiele, T and Boon, N 2014, 'Microbial Odor Profile of Polyester and Cotton Clothes after a Fitness Session', *Applied and Environmental Microbiology*, 80(21), pp. 6611-6619
Chaturvedi, S, Colmenares, E and Mundim, TS 2011 'Knitectonics', *integration through computation*
Cruz, M and Beckett, R 2016, 'Bioreceptive design: A novel approach to biodigital materiality', *Architectural Research Quarterly*, 20, pp. 51-64
Dupraz, C, Reid, RP, Braissant, O, Decho, AW, Norman, RS and Visscher, PT 2009, 'Processes of carbonate precipitation in modern microbial mats', *Earth-Science Reviews*, 96(3), pp. 141-162
Ellis, T, Adie, T and Baldwin, GS 2011, 'DNA assembly for synthetic biology: from parts to pathways and beyond', *Integrative Biology*, 3(2), pp. 109-118
Esnault Filet, A, Gadret, JP, Loygue, M and Borel, S 2012 'Biocalcis and its Applications for the Consolidation of Sands', *Geotechnical Special Publication*, pp. 1767-1780
Hardy, DA, Anastasopoulos, I, Nashed, MN, Oliveira, C, Hughes-Riley, T, Komolafe, A, Tudor, J, Torah, R, Beeby, S and Dias, T 2019, 'Automated insertion of package dies onto wire and into a textile yarn sheath', *Microsystem Technologies*
Hills, RL 1989, 'William Lee and His Knitting Machine', *Journal of the Textile Institute*, 80(2), pp. 169-184
G Lisansky, S 2007, 'Fungi in biological control systems Edited by M. N. Burge, Manchester University Press, 1988, pp. 269, price £39.50. ISBN 07190 19796', *Journal of Chemical Technology and Biotechnology*, 48
Mankodi, DH 2011, 'Developments in hybrid yarns', *Specialist Yarn and Fabric Structures: Developments and Applications*, pp. 21-55
McQuaid, M 2009, 'From craft to production: Technology transfer in extreme textiles', *Journal of the American Society for Information Science and Technology*, 60(9), pp. 1920-1922
McQueen, RH, Laing, RM, Brooks, HJL and Niven, BE 2007, 'Odor Intensity in Apparel Fabrics and the Link with Bacterial Populations', *Textile Research Journal*, 77(7), pp. 449-456
Padaki, NV, Alagirusamy, R and Sugun, BS 2006, 'Knitted Preforms for Composite Applications', *Journal of Industrial Textiles*, 35(4), pp. 295-321
Steed, J 2016, 'Hand Knitting in a Digital Era', in Nimkulrat, N, Kane, F and Walton, K (eds) 2016, *Crafting Textiles in the Digital Age*, Bloomsbury Academic , p. 25
Tamke, M 2015 'Designing CNC knit for hybrid membrane and bending active structures', *Textiles composites and inflatable structures VII: proceedings of the VII International Conference on Textile Composites and Inflatable Structures, Barcelona, Spain. 19-21 October, 2015*, pp. 281-295
Thiemann, W 2007, 'The Emergence of Life. From Chemical Origins to Synthetic Biology. By Pier Luigi Luisi', *Angewandte Chemie-international Edition - ANGEW CHEM INT ED*, 46, pp. 823-824