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Systems for transformative textile structures in CNC knitted fabrics – Isoropia

Mette RAMSGAARD THOMSEN*, Yuliya SINKE BARANOVSKAYA*, Filipa MONTEIROa, Julian LIENHARDb, Riccardo LA MAGNAb, Martin TAMKE*

*CITA, 1435 Copenhagen, Denmark, martin.tamke@kadk.dk
a A. Ferreira & Filhos SA, 4815-901 Caldas de Vizela, Portugal
b Str.ecture GmbH, 70176 Stuttgart, Germany

Abstract

Extending recent work on Form Active Hybrid Structures of Active Bend and CNC knitted (Computer Numerical Control) tensile members we present a set of innovations in design and manufacturing, which together allow to build structural systems, that morph across multiple structural states. While state of the art tools and fabrications methods in textile hybrid structures provide architects and engineers with means to adopt the geometry of a chosen textile system to the requirements of a given site, constraints in design thinking, tools and manufacturing however still limit the ability to change the spatial and structural qualities and expressions within a textile object. The potentials of our developments to create new spatial expressions and atmospheres in textiles structures are demonstrated and evaluated through the large-scale installation Isoropia designed and built for the Danish Pavillion in the 2018 Venice Architectural Biennale.

Keywords: Architecture, Digital Design, Bending Active Textile Membrane Hybrids, Digital Chain - Integration of Design, Simulation and Fabrication, CNC Knit

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1. Introduction

Tensile membrane structures are per se customized, as the shape of the membrane can only be determined through the process of form finding. In here the final membrane shape emerges as equilibrium of forces. As result tensile membrane structures are usually one-offs, designed and engineered specifically to the context, they are situated in, and fabricated to project specific specifications of predominately non-standard elements. Current state of the art membrane projects, are however dominated by a desire to repeat the same or similar elements, restricting the expression and spatial potential, which resides in the bespoke nature of membrane technology. In this paper we propose to use digital workflows for the design and fabrication of bespoke materials and elements to create in an efficient manner membrane architectures, which create radical new spatial atmospheres, exemplified in the 2018 installation Isoropia (Fig. 1).

In architectural fields outside of membrane structures new spatial experiences and expressions have in the last decade been enabled through the use of non-standard design and fabrication methods. The success of these designs is based on the implementation of computational techniques in design and analysis and an integration of digital design and digital fabrication (Tamke & Thomsen, 2009).

These digital design methods and workflows have enabled new spatial and tectonic solutions across all scales (Fig. 2-6) in which elements change and morph in order to change the atmosphere and expression for the humans within. As shown in the 2009 CITA exhibition design for “It’s a small World” a non-standard design approach allows structures to adapt seamlessly to different scales and environments and act as a physical mediator between spatial requirements. Furthermore the underlying computational approaches provide the base for future
highly material efficient structures, which rely on the total integration of design and robotic manufacturing (Nicholas, Zwierzycki, Nørgaard Clausen, Hutchinson, & Thomsen, 2017; Solly, Frueh, Saffarian, Prado, & Menges, 2018).

In the field of tensile architectures the use of non-standard approaches has been tested early on in small scale academic prototypes, such as the 2007 AA Component Membrane installation and related work (Hensel & Menges, 2008). However similar site and human scale specific installations, that are based on the morph of the size and shape of membranes across the structure, have until now not seen a wide implementation in the field. Instead discrete and varying membrane fabric elements of same size are repeated, as in the case of the King Fahad National Library (2014) (Dupont, 2014), or an intended morphing expression is created through a combination of a customised steel structure and standard membrane elements, as in the Nizhny Novgorod Stadium (2018) (Bernert, 2018).

While the authors of the latter structure do not reveal the reason, why their design shifted from a non-standard approach towards the pattern cut of the membrane elements to standard ones, accounts from small scale structures with non-standard approaches to geometry and detailing (Hensel & Menges, 2008), point at the labor intensity in design, simulation, fabrication and assembly as a challenge. Moreover, the inherent stiffness of traditional laminated membranes limits the scales by which it can be applied, as the need for seams to assemble patches to achieve double curvature and integrate detailing further limits the scales by which the membranes can be used.

New opportunities for spatial expression and tactile experiences emerge through the integration of design, analysis and fabrication combined with the shift of the textile system from weave to CNC-knit (Ahlquist & Menges, 2013; Popescu et al., 2018; Sabin, 2013; Thomsen et al., 2015). The inherent flexibility of knit, the ability to integrate shaping and detailing in the textile fabrication process opens especially opportunities for designing membranes at the smaller scale of state of the art membrane architecture, as in Ron Herrons Imagination Building (Lyall & Herron Associates, 1992). Current application of CNC knitting in the field have focused on
small scale prototypes, but didn’t engage in building scale or devised knitted textiles a role as structural member, as needed in Form Active Hybrid Structures of Active Bend and Tensile members (Thomsen et al., 2015).

1. Isoropia - Outset and framework

Isoropia, which in Greek means balance, equilibrium and stability, is a 35m long structure made from 41 custom CNC knitted patches of up to 7m length for the 2018 Venice Biennale Installation. The textile membrane is set in structural equilibrium with bend glass fibre rods of varying thickness and strength.

In this paper we ask how state of the art materials and structural systems, design and fabrication workflows can create avenues for new spatial experiences in textile architecture. Detailed questions of digital design and analysis workflows in isoropia have been discussed in a previous publication (La Magna, Fragkia, Noël, Baranovskaya, & Thomsen, 2018).

The structure creates a spatial and structural continuum through the Danish Pavilion, forming differentiated outdoor canopy structures on the two outer sides and a vaulted space in the interior in a reaction to the specific program and sites (Fig. 7):

Fig 7. Architectural concept of Isoropia. 1) The southern exterior part (left) welcomes visitors to the Biennale and creates a canopy like structure guiding visitors into the Danish Pavilion. 2) The interior passage (middle) is the only entrance to the Danish Pavilion. The aim was to create a dense textile space, which creates curiosity on side of the visitors, allows them to slow down, study movies and text about the installation and finally redirects them into the further exhibition of the pavilion. 3) The northern exterior part (right) is directed towards the lively cafe zone of the Biennale and creates an shading entrance canopy, which adapts to the rhythm of the colonade of the existing Danish Pavilion.
Further forming requirements have been:

- the status of the Danish Pavilion as quasi listed building, which prohibits irreversible modifications to the construction
- the need to connect the structure to “Danish ground” only, which prohibited any ties to the directly surrounding “Italian” ground and the large amount of ca. 150,000 visitors, which required a sturdy construction and detailing in compliance to structural and historical conservation code, that had to be documented in a building permission to the authorities
- the pavilion had to work at day and night, which required the integration of artificial lighting.

Most important of all the time given from commissioning of the installation to its completion was only 4.5 months.

1. Isoropia solutions

The conceptual answer to the total amount of ideas and demands, was to create a structure, which can morph and adopt on relatively small scale yet high level and quality of textile surfaces and detail. In order to overcome the above listed constraints we had to devise new solutions on several levels. These are highly interconnected in terms of the processes in design, analysis and fabrication as well across scales.

1.1. Structural system - Bending Active Textile Hybrid

The building system employed for the canopy falls into the category of bending-active membrane hybrids (Ahlquist, Lienhard, Knippers, & Menges, 2013). These are defined as systems that achieve equilibrium through the combination of bending-active elements (the GFRP rods) with purely tensile elements (the membrane patches and cables), hence the hybrid nature of the structure. The bending-active elements provide the required mechanical supports to prestress the tensile elements, which in turn lock the bent rods into position. In this way, a subtle equilibrium solution is achieved in which the interdependency between the individual components is necessary for the stability of the structural system. The shape of the canopy is therefore the result of the interplay of internal forces conveyed by the individual structural elements.

In order to morph, the Isoropia structural system shifts from a cabilnet system on the exteriors, which pre-stresses and stabilises the structure, to a tensegrity-like structure in the interior in which compression elements pre-stress the knitted membrane (Fig. 7). Each arrangement posed a specific challenge in terms of analysis and assessment of the structural behaviour.
The outdoor areas derive their shape from the mutual force interaction between the bent rods, tensile Dyneema® membrane and Dyneema® cables. The only support being the dedicated steel fixtures on the building’s wall. The rods with diameter and wall thickness (24.3/20.3mm and 26/19mm), bespoke to local performance requirements, cantilevered outwards and were kept in position solely by the prestressed tensile elements (Fig. 7). In terms of form-finding and structural analysis, this area presented particular challenges due to the high nonlinearities deriving from the minimal amount of supports and mechanical constraints in the system.

Finally the listed building status of the Danish pavilion coupled with the bending-active hybrid nature of the canopy, pushed for solutions that reduced to the bare minimum the interventions on the surroundings and consequently the support areas that could be used to secure the structure.

1.2. Design system

For the purpose of the project these constraints were translated into a dedicated design system (Gengnagel, La Magna, Ramsgaard Thomsen, & Tamke, 2018) that seamlessly connected the digital design pipeline used for geometrical exploration, based on Projection Dynamics (Bouaziz, Martin, Liu, Kavan, & Pauly, 2014), with an intermediate Isogeometric Analysis tool (Längst, Bauer, La Magna, & Lienhard, 2018), which provided frequently feedback on the structural performance of the canopy and finally a robust and detailed analysis using more established tools for simulation (Julian Lienhard, Bergmann, La Magna, & Runberger, 2017). In this way, the behavior of the structure could be constantly monitored during the development of the project, providing valuable information to all the parties involved throughout the conceptual and development phases.

1.2.1. Digital Design Workflow

The developed continuous membrane system is based on a single principle structural unit, consisting of a pair of bend GFRP rods (Beams), which carry a connecting membrane, stressed by cablenets or compression sticks. Through variations, of parameters in this basic units, such as the width between the supporting rods, their lengths and the interposition of the fabrics in relation to the rods, a continuous yet adapting structure is possible.
Around this basic parameters a generative design pipeline using Kangaroo2 (Quinn et al., 2016) was built (Fig 8). This setup allowed rapid design variations, through changes of only a few parameters, such as the beam locations in space (A), the beam length (B) and Z-position.

E) All quads get discretized in custom resolutions, as either single or double layer membranes. The amount of coverage of the second layer is increasing gradually F)The cablenets and the amount of pulling points are introduced. G)The interior membranes are generated and compression sticks are introduced and iteratively optimised in order to find an equilibrium position in the textile. H)External constraints for the relaxation are introduced: anchors, external tension ropes, links to the ceiling in the interior and back tension ropes for the non-cablenet units. I) Kangaroo Force values are applied to the goals of the digital design tool pipeline and the overall shape is found.

1.2.2. Analysis Workflows

The digital design tool provided an agile platform for quick design explorations and geometrical variations of the canopy throughout its conception and development. Though, the high level of documentation requested by the authorities, a detailed analysis of the structure was necessary in order to assess its performance under high wind loading and its effects on the surroundings, especially the reaction forces exerted by the canopy on the support areas fixed to the building. A dedicated workflow between the design and analysis was set up to quickly provide feedback to the design process.

Kiwi3d, a new tool for Isogeometric Analysis, was used for intermediate quick analysis. In particular, Kiwi3d incorporates modules for linear and nonlinear analysis, as well as form-finding based on the URS (Updated Reference Strategy) method (Philipp, Breitenberger, D’Auria, Wüchner, & Bletzinger, 2016). To speed up the transfer between the two platforms, a
geometry processing workflow was set up which took care of the discrepancies between the geometric models. This meant converting discrete lines and surfaces into continuous spline and NURBS patches through interpolation of the nodes. This geometry conversion was robust and reliable and an analysis of the full building process of the canopy could be simulated: the bending of the GFRP rods, the attachment and form-finding of the membrane patches and linking the cables to the membrane and prestressing it. Besides this initial assessment of the structural behaviour under wind loading (930 mm vertical deformation for wind suction, 640 mm vertical deformation for wind pressure) and the corresponding reaction forces took place in Kiwi3D.

The analysis of the canopy was completed by running a Finite Element simulation on the final design (SOFiSTiK coupled with the dedicated Grasshopper plugin STiKbug) (J. Lienhard, La Magna, & Knippers, 2014). This step was necessary to validate the intermediate results using well-established tools which have been extensively tested both in research and in practice. The Finite Element tools allow for a very detailed description and simulation of the structural behaviour, giving the analyst the possibility to incorporate advanced aspects such as long-term behaviour and plasticity. Specific to this case, compressive springs were added in the final simulation model to take into account the contact between the bending-active rods and the building’s walls, an aspect that needed to be verified due to the scrupulous requirements of the organization.

1.3. Material Systems

In Isoropia we further develop the inter-scalar approach first suggested in the Hybrid Tower projects (Holden Deleuran et al., 2015; Thomsen et al., 2015). Here, design takes place at multiple scales from the overall structural system, to the single patch, the implemented knit structure and down to fibre selection and fibre surface.

1.3.1. Knitted membrane: an inter-scale approach

In difference to Hybrid Tower, in which a single patch design is repeated to achieve the rotational geometry, Isoropia works with mass customised patches. As the structure morphs from canopy to vault and back again and as it twists through the Danish Pavilion building, each patch is differentiated both in size and shape. This differentiation creates variances in the patch design from a variation of protruding cones and slits (Fig.9).
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Isoropia also further develops the innovative membrane design from Hybrid Tower, where we detailed the membrane through tubular jersey for double surface channels, interlocking for reinforcement parts and holes for tying and pre-stressing (Tamke et al., 2016). Isoropia further differentiates between various knit patterns within the patch surface (Fig 10). Initial tests using only one base knit pattern (Piquet Lacoste) revealed to be too tight to achieve the strong three dimensionality needed for the cones, which provides together with the cablenet structural depth and capacity. To increase cone depth we defined a fourth stitch pattern, in which the interlocking between needles is less, therefore allowing more flexibility of the yarn and better deformation. This fourth stitch pattern is introduced in star-shaped zones around the cones grading the material locally for performance.

Fig 9: Outline drawings of all patches produced for the three zones of Isoropia. The graph lines surrounding the bounding boxes indicate the amount of elasticity in areas of the patches through combination of different knit structures.

Fig 10: The in Isoropia used knit patterns (from left: tubular, piquet lacoste, interlock, piquet)
The double patches are assembled using a knit logic (Fig. 11&12). By linking the two surfaces together, in the way that garment patches are linked together, we employ a knit stitch and use the same fibres as in the patches. In this we achieve similar performance of the assembly stitch as in the overall patch allowing better pre-stressing of the membrane.

1.3.2. Fibre system - manufacturing bespoke knit

At fibre level the material, machine requirement and final textile structure had to be considered in order to achieve a promising textile system, which could handle the variations in pattern and mechanical stress that characterizes Isoropia. It was further important, to create a welcoming and soft haptic experience for visitors who touch the fabric, unlike the plastic nature of state of the art building membranes. From a limited range of available high performance yarns, ultra high molecular weight polyethylene yarns Dyneema® SK65 was selected due to its enhanced mechanical properties specifically 3.3-3.9 GPa of Tensile Strength; 109-132 GPa of Tensile Modulus and 3-4% Elongation at Break (Fig. 13&14)

Fig 11-14: Linking using Dunkermotoren linker (BG83 14GG), Dyneema® SK75 220DTex

1.4. Fabrication Systems

In Isoropia the development of design, knit specification and fabrication system ran in parallel and each step of this rapid process was evaluated in 1:1 prototypes. This required to have early on an automatic link between the digital design tool at CITA, and the CNC knitting machines at the textile producer AFF.

1.4.1. Digital Fabrication Interface

The interface between design and production takes place through bitmap files (Thomsen et al., 2016). These files are automatically generated from planarised meshes of the digital design system (Fig. 15)
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Fig. 15: Workflow for the Digital Fabrication Tool: A) A 2D mesh with identical mesh topology to the formfound 3d mesh is generated. B) The protrusion of each cone is “relaxed” into a simplified 3d mesh, as the cones are formed as the result of textile stretch only. The outer edge lengths are maintained. C) The internal and external edges of the 3d mesh are measured and used as constraints for a K2 relaxation of the 2D mesh with a 0.01m tolerance for the output edge lengths. D) A best fitting bounding box is generated and tested against the max width of the CNC knitting machine. E) The 2D mesh and the transposed cone centres serve as base for the automated specification of the boundaries of areas with different knit structures (rods channels, details for the lighting details, reinforcement edge and the expandable cone stars, large slits). Visual feedback is provided on the relation between zones of different stretch (Piquet and Piquet Lacoste). F) Colours are assigned to the different areas. The lines in linework was set a colour. H) In order to accommodate the non-square nature of knit stitches, a non-uniform scaling is performed. I) Lineworks is processed with Squid (Grasshopper Plug-In, developed at CITA by Mateusz Zwierzycki), filled with predefined colours and exported as bmp.

The development of the digital fabrication workflow did take place through iterative testing and prototyping of samples in increasing size (Fig. 16). 1:1 prototyping of the system was instrumental in order to understand and measure the interplay of all elements and materials across all scales, instead of working on assumptions gained from isolated tests. Each prototype allowed the project to leap to a more reliable level and gain validated correction values for the parameters in the design and fabrication workflow.
1.4.2. Producing CNC Knit - Machines

The complexity of Isoropia on knit level required a high degree of freedom on side of production machinery. For this a Shima Seiki M183514 14GG flat knitting machine and APEX3 software was selected, due to their ability to interface on level of design and programming code (Barfield, 2015). The process of converting the bitmap knit information from the design level to CNC knitting code (Fig. 18 & 19) entailed that the single colour fills of the bmps were assigned a smaller scale pixel pattern, which contains a particular information for every single needle. This required the computationally powerful SHIMA SEIKI computer units and novel processing steps and design planning for knitting procedures. Some challenges were faced regarding the yarn flow, the structural detail of the textile area itself and the pre-defined outer shape. Structural detail meaning the interfaces of the different structures in the knit (Fig. 15). Techniques had to be developed in order to absorb or spread tension between structures where needed and also allow a proper knitting flow whenever the knit code changes between different structures. These three distinct textile architectures had to be precisely programed and tested to resist mechanical solicitations without compromising neighboring structural requirements. Though the project was based on previous collaborations (Tamke et al., 2016) any new development posed challenges. The use of the inelastic and hence demanding Dyneema® yarn required for instance an adjustment of the knitting machine in order to be able to knit on a high speed without mistakes or damages to the machine. But as well interdisciplinary challenges occurred, when new processes, as the linkage of two single layer into a double membrane were introduced. In here the existing work procedures and the lack of integrated markers on the fabric of the positions to link the fabric created a situation where the fabrics were linked wrong, which resulted in a non-matching assembly. Fortunately the issue could be very easily solved by simply delinking the fabrics and linking them once again in the right places.
2. Conclusion and Potentials

The realisation of the bending-active membrane hybrid Isoropia was only possible, through an integration of the Structural, Design, Material and Fabrication system. This transdisciplinary and interscalar approach allowed us to design and build a morphing structural membrane system in only 4.5 months, which delivers new spatial experiences and a new level of detailing to the field of small scale membrane structures. Isoropia is until today the largest structure made in preprogrammed CNC-knit, with every single membrane being unique (Fig. 20-22).

The approach chosen in Isoropia opens up opportunities for new design expressions in textile architectures and an integrative approach towards other building elements. Isoropia morphs between two very radically structural systems and spatial expressions: from a more normative outer appearance to the radically textile space in the inner area. A unified impression is created through the use of similar design features - the textile cones - in both systems and the ability to specify gradual shifts in families of elements and materials.
The ability to morph provides the structure with modes to adapt and create highly local interfaces to the existing buildings. This was beneficial for the design of structures in historic context. A further factor, which contributed to the minimal invasive character of Isoropia was, that we could avoid tension connections to the existing structures, as the prestressing of the membranes was provided within the hybrid structure itself.

Despite being a first of its kind, the overall installation of Isoropia took only 8 days. Most of the time was used to install the infrastructure, such as electrics and support, while the actual assembly and tensioning of the hybrid structure only hours. This shows, how the integration of functionality and performance in elements and materials, allows to minimise the overall complexity and costs of building, which would else arise through on-site fabrication, assembly and the handling of many parts.

During the exhibition we observed, that most of the more than 100,000 visitors touched the textile surfaces of Isoropia with interest and pleasure. CNC knit is able to create surface qualities on level with apparel, even when it is made from high performance yarns.

Finally Isoropia is giving rise to an environmental friendly architecture and smart production strategy through CNC knit, which is able to address zero waste and low labor intensity production, deliver elements with highly customised shapes, functions and behaviours and new freedom in design of membrane architecture. In this aspect Isoropia is a stepping stone and the exploration of designed movement of similar hybrid structures, the further integration of lighting and the production of non-manifold surfaces are obvious next steps.

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