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DESIGNING CNC KNIT FOR HYBRID MEMBRANE AND BENDING ACTIVE STRUCTURES

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Summary. Recent advances in computation allow for the integration of design and simulation of highly interrelated systems, such as hybrids of structural membranes and bending active elements. The engaged complexities of forces and logistics can be mediated through the development of materials with project specific properties and detailing. CNC knitting with high tenacity yarn enables this practice and offers an alternative to current woven membranes. The design and fabrication of an 8m high fabric tower through an interdisciplinary team of architects, structural and textile engineers, allowed to investigate means to design, specify, make and test CNC knit as material for hybrid structures in architectural scale. This paper shares the developed process, identifies challenges, potentials and future work.

1 INTRODUCTION

Current structural membranes are based on coated fabrics or films, produced in homogenous lanes, which are cut in pattern and seemed, before details for the interfacing with other parts are applied. The current approach towards the manufacturing of a highly bespoke membrane is rooted in the limitation of the underlying process of weaving. Knitting on the other hand is characterised by the ability to create highly heterogeneous materials and bespoke figures. With industrial CNC knitting machines, it is for instance possible to knit to shape, introduce details directly into the material, combine and change fibres of different strength or change the structure of the material at any place. The material allows hence for highly bespoke textile surfaces [1]. Within knitted surfaces, the complexity of detailing, material properties and production can be collapsed into the material itself.

The design and production of a 8m high textile tower (Fig.1) made from bending active load carrying GFRP rods and restraining membrane surfaces explored the potential of CNC knit surfaces in architectural application, especially for temporary installations. The Tower was developed and produced in the period autumn 2014 to spring 2015 and assembled and exhibited in the courtyard of the Danish Design Museum in April to May 2015. The development of the tower is based on previous research and expertise of the partners in their respective fields. The actual production of a physical demonstrator required however to synthesise the respective fields and created insights in the systems, tools and processes, which need to come into place to realise a novel set of hybrid structures of bespoke CNC knit membranes and active bending elements.

Figure 1: The Tower in the Courtyard of the Danish Design Museum.

Figure 2: The interior of the Tower is characterised by the tensioning system and the resulting cone-like membranes. Photo: Anders Ingvartsen.

2 THE TOWER - A HYBRID STRUCTURAL SYSTEM

Active bending is the intentional use of elastic deformation as a shaping process for linear or planar structural elements. The main motivation for its use lies in the simplicity of creating curved elements for exciting and versatile architectural forms but with a low demand on production energy and material consumption [2, 3]. The Tower extends previous research into bending active structures with membrane surfaces on the level of scale and through the integration of details into the membrane. The most prominent examples of bending active structures, the Multihalle Mannheim (1979) by Mutschler, Langer and Otto [4] and recent continuation of this work by Bavarell [5], used braced grids made from bend element. The membrane provides enclosure, but does not contribute on the structural level. Ahlquist and Lienhard have introduced structures on installation scale, as in the Tour de l'Architecte (2012) in Monthoiron/France [6], where a limited number of surfaces stabilise bending members. The structural pattern of the tower under discussion in this paper consist however of 64 individual membrane surfaces and even more bending active rods. Our research comes hence closer to the amount of interacting discreet elements found on building scale.

As elastic bending generates residual stresses, the choice of material, cross-section height and curvature is limited. However, in hybrid systems the selection of the profiles' properties can be optimized for the bending process, since under external loads the restraining elements drastically improve the global stiffness of the hybrid structure. Previous research has shown that the application of membranes as restraining elements has several advantages in comparison to typical cable based restrained systems [7,8]. Physical and numerical test have emphasized the importance of the construction details- especially the joining of membrane and actively bent rods- of such hybrid systems for their global bearing behavior. The stiffness of membrane restrained systems is i.e. significantly reduced, if the connections to the bent element and the edge-cable allows sliding – a strong connection and channels for the bending active element are recommended.

The tower explores furthermore textile joints made from high tenacity knit as softer alternative to common steel joints in active bending structure. These create obstructive force maxima within coupled bending active elements [9].

The basic concept of the hybrid structure is to create a membrane reinforced by a dense grid of overlapping bending and compression stiff GFRP rods, continuously integrated in the membranes pockets and channels. This necessitates a fine balance between softness and rigidity in the material, in order to create a structure flexible and bendable - capable of responding to changing conditions of the environment.

The structural system of the tower consist of a double curved grid- shell like structure made of slender overlapping rods, embedded in a membrane made from high tenacity yarn in the surface of the shell in combination with a cable based restraining system perpendicular to the surface of the shell (Fig. 2). This second restraining system pulls the centre of each membrane patch radially to the tower central axis. This results in a spoke wheel effect which provides horizontal stiffness, braces the cylindrical gridshell and increase the load capacity of the overall system significant. The dominant load cases for such a vertical oriented lightweight structure are the agency of wind with an exponential increase of loading in height and a risk for dynamic complications. In the horizontal section the cylindrical shape of the tower leads to typical wind load distribution with less pressure windward, high suction sidewise and lower suction leewards (Fig 3).

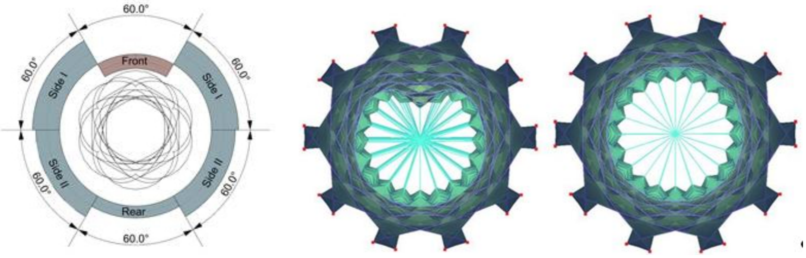


Figure 3: FE simulation of the tower with wind load distribution and bracing system. Deflected state under windload from front in the middle and relaxed state on the right.

Under such loading the membrane is supposed to act in two ways: as a tensile element to transfer tensile forces on the windward side and as restraining systems to prevent all curved compression elements for further bending and buckling in plane. The radial restraining cable system has also multifunctional purposes: as a form-stabilisation system the spoke wheels are preventing any further bending out of plain of the rods while they give the membrane patches a strong local double curvature, increasing the pre- stress of membrane.

3 DEVELOPMENT OF KNIT STRUCTURE AND INITIAL TESTING

The tower project assigns the textile material key roles:

- Reduction of fabrication effort through: Knitting of patches with bespoke shapes instead of cutting and patching
- Reduced assembly time through minimisation of amounts of seams and integration of detail
- Bracing of structure under load: use of high tenacity yarn
- Constraining the movement of bending active rods: Integration of detailing into the membrane (tunnels and pockets)
- Minimisation of pattern cut: Use of material stretch to achieve double curved surfaces
- Designed material behaviour under forces: development of bespoke knitting structure

Commonly used knit is however characterised by high stretch, low strength, antistrophe behaviour and non-linear behaviour. To develop sufficient behaviour and detail through the local variation of knit structure and fibre, motivated the research on the material level.

Weft knitting technology was used to produce the fabric for the tower. As the tower is exposed to various weather conditions and submitted to various stresses and strains, high performance yarns based on polyamide (PA), polyester (PES) and polypropylene (PP) are good candidates The lower moisture absorption, average elasticity and very high resistance makes high tenacity polyester here an especially well suited.

In terms of knit structure single cardigan, half cardigan, rib, interlock, jersey and piquet Lacoste were investigated in tests, where only the latter two showed the required transparency and low level of elasticity. During the knitting of samples on a on an Stoll CMS 320 TC electronic flat knitting machine it became obvious that the loop length and the PES yarn linear density (55 and 110 tex) (Table 1), were the crucial parameters to control the fabrics elasticity and porosity. The tensile behavior of the samples was studied by Grab method, according to NP EN ISO 13934-2 standard, on a Hounsfield universal testing machine. Five specimens (100x200 mm) of each sample were tested in coursewise and walewise directions, with a crosshead speed of 100 mm/min.

The obtained results show, that the structures produced with higher linear density yarns present higher tensile strength. When comparing Jersey and piquet Lacoste structures, for the same linear density, it appears that, in the coursewise direction, piquet Lacoste structure has higher tensile strength and lower elongation – making it the structure of choice for mechanical behavior, but also for visual aspects.

The pockets, channels and reinforced areas in the membrane were developed on the base of a ground structure (piquet Lacoste) using the machines abilities for individual needle selection, take-down adjustment during knitting, loop transfer and racking.

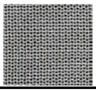
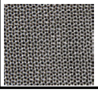
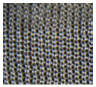
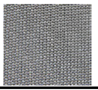
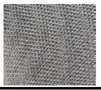
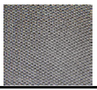
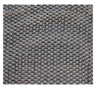
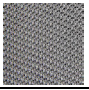
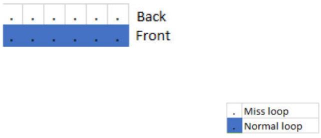
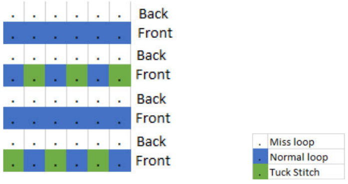
		Jersey				Piquet Lacoste			
		NP: 10,5	NP: 11	NP: 12	NP:11	NP: 10,5	NP: 11	NP: 12	NP:11
Pictures									
Pattern									
Composition [%]		PES HT 100	PES HT 100	PES HT 100	PES HT 100	PES HT 100	PES HT 100	PES HT 100	PES HT 100
Yarn Type		multifilament	multifilament	multifilament	multifilament	multifilament	multifilament	multifilament	multifilament
Linear density [tex]		55	55	55	110	55	55	55	110
Loop length (lu)/100 wales [cm]		0,48	0,53	0,63	0,6	3,77	4,16	5,08	4,59
Density	wales/cm	10,4 (5%)	9,2 (4%)	8,2 (5%)	8,4 (7%)	8,4 (6%)	6,8 (6%)	5,8 (7%)	6,0 (0%)
	courses/cm	16,4 (3%)	14,0 (0%)	10,0 (0%)	13,0 (0%)	12,4 (4%)	11,0 (0%)	7,2 (6%)	11,0 (0%)
Tensile Strength	Maximum strength at break [N] - walewise direction	697,18 (9,48%)	669,34 (8,49%)	493,52 (8,75%)	1374 (6%)	566,27 (6,27%)	440,28 (12,25%)	378,76 (5,98%)	1122,5 (8%)
	Extension at break [%] - walewise direction	87,18 (16,98%)	72,12 (3,64%)	67,13 (7,10%)	91 (14%)	106,96 (1,93%)	90,43 (11,67%)	76,67 (5,37%)	128 (9%)
	Maximum strength at break [N] - coursewise direction	604,38 (6,23%)	454,20 (9,43%)	333,12 (8,05%)	1026,88 (7%)	819,07 (2,94%)	645,62 (5,44%)	433,96 (8,44%)	1417,00 (7%)
	Extension at break [%] - coursewise direction	107,78 (1,76%)	119,08 (7,61%)	153,19 (8,88%)	111,16 (5%)	71,25 (4,06%)	75,70 (3,92%)	94,58 (3,13%)	85,52 (6%)

Table 1: Mechanical and Structural Characterization of the produced samples

4 TESTING OF THE BIAXIAL MATERIAL BEHAVIOUR OF KNITTED SURFACES

It was crucial for the design and simulation of the tower to know the behaviour of the knit under biaxial load. Currently no testing procedure exists for the biaxial testing of knitted fabrics, which was hence performed according to the testing procedure of the Japanese Standard MSAJ/M-02-1995 [10] for biaxial testing of woven fabrics. Herewith, the "fictitious" elastic constants of the material could be determined.

The main characteristic of MSAJ/M-02-1995 is that five different predefined stress ratios warp:fill – 1:1, 2:1 1:2, 1:0 and 0:1 – are consecutively applied on a cross shaped test specimen with the yarns parallel to the arms of the cross. During the loading and unloading procedure, the load ratio warp:fill is held constant. The maximum tensile test load is fixed to ¼ of the maximum strip tensile strength of the fabric direction with the lower strength. The result of this test procedure is a stress-strain-diagram. From this complete set of test data ten stress-strain-paths can be extracted – one for each yarn direction for the five load ratios. MSAJ/M-02-1995 recommends to determine on the base of the five ratios one single design set of elastic constants from the extracted stress-strain-paths stepwise in a double step correlation analysis.

In the frame of this project two different types of Piquet Lacoste Structure CNC knitted fabrics were tested in the Essen Laboratory for Lightweight Structures (ELLF), University of

Duisburg-Essen: NP11 with linear densities of 110 tex and 55 tex. For two reasons it was not possible to perform "classical" biaxial tests according to MSAJ/M-02-1995 with this material:

The geometrical dimensions of the available material were limited to a length of 1600 mm (wales, machine direction) and a width of 700 mm (course, transverse direction). Herewith, the ELLF-standardized cross shaped test specimens (1500 mm x 1500 mm) to be used in the ELLF biaxial testing machines could not be cut.

As the material is knitted, cutting it in a cruciform shape was not possible without any additional auxiliary seams in order to avoid unravelling of the material.

In total, four biaxial tests were carried out, three for the 110 tex and one for the 55 tex material. Due to the aforementioned reasons, the "classical" cruciform geometry of the biaxial test specimen was modified to the test specimen geometry presented in Figure 4. As the material behaviour was unknown, a stepwise procedure was chosen to identify the biaxial material characteristic of the CNC knitted fabric. In a first step the 110 tex material was investigated by performing two MSAJ-tests with an upper maximum tensile test load of ¼ of the maximum strip tensile strength of the material and finally one with a reduced maximum tensile test load of ca. 17.5 % of the maximum strip tensile strength. The reduction became necessary due to the fact that the material exhibited very high strains and transverse contractions in both directions in the load ratios 2:1, 1:2, 1:0 and 0:1. As the uniaxial load ratios still showed very high strains and transverse contractions, it was finally decided to perform additional uniaxial tests in the biaxial testing machine whereby the zero stress direction was unclamped. For the 55 tex material the last test procedure was applied with one modification: the 1:0 and 0:1 load ratios were only applied in the pure uniaxial testing with unclamped zero stress direction.

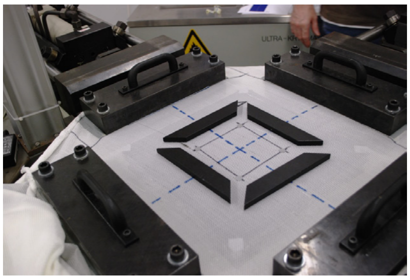


Figure 4: Biaxial testing of the CNC 55 tex knitted fabric with modified test specimen after applying the prestress [© ELLF]

Exemplary for the 55 tex material, Figure 5 presents the loading sequence according to MSAJ/M-02-1995 without the 1:0 and 0:1 load ratios and the stress-strain-diagram as a result of the biaxial test.

From the complete set of test data six stress-strain-paths were extracted – one for each yarn direction for the three load ratios. Together with the uniaxial tests, one single design set of elastic constants from the extracted stress-strain-paths were determined stepwise in a double step correlation analysis. In the first step each curved loading path was substituted by a straight line. In the second step the slopes of the straight lines obtained in the first step were modified in such a way that they satisfy the equations of the assumed linear-elastic constitutive law using a correlation analysis routine programmed at the ELLF, University of Duisburg-Essen [11, 12, 13].

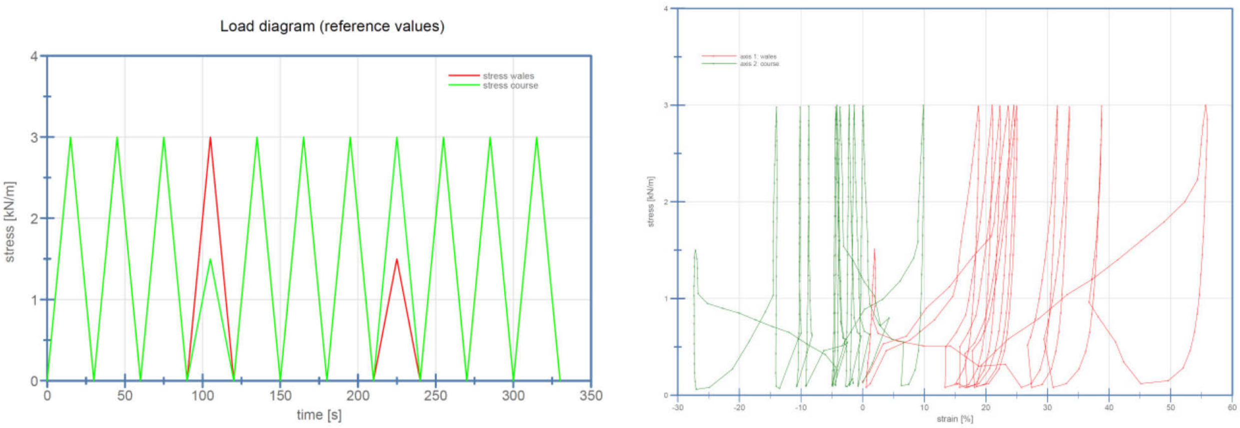


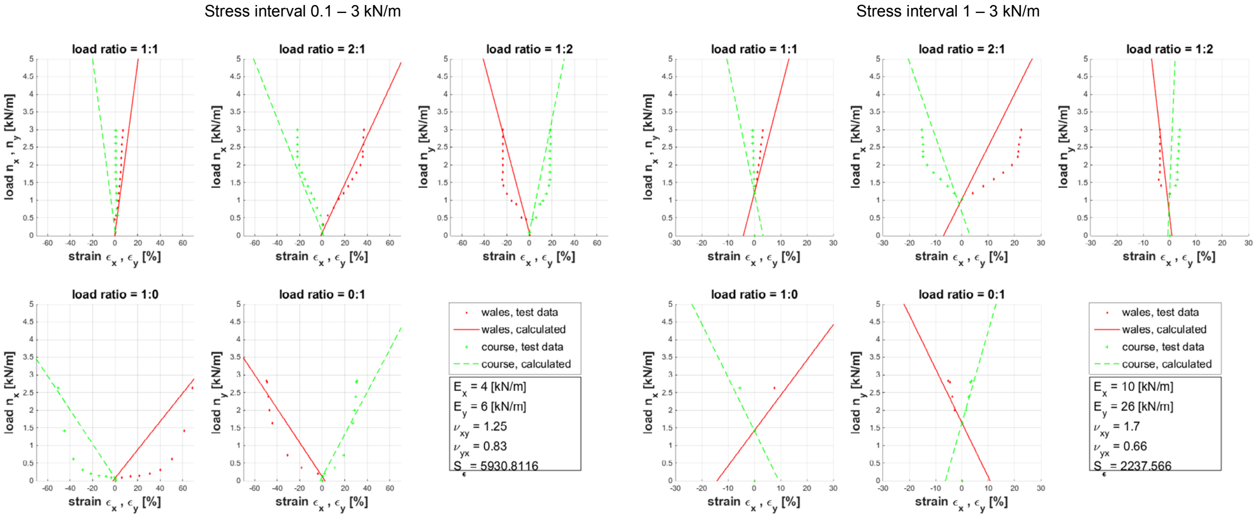
Fig 5.1 & 5.2: Exemplary loading sequence according to MSAJ/M-02-1995 without the 1:0 and 0:1 load ratios (left) and the stress-strain-diagram as a result of the biaxial test (right) [© ELLF]

The Piquet Lacoste, NP 11, 55 tex material shows an approximately bilinear behaviour with a significant change of stiffness in the stress range of 0.5 - 2 kN/m, so that two evaluations for different stress intervals were conducted:

(1) stress interval 0.1 - 3 kN/m and

(2) stress interval 1.0 - 3 kN/m.

As a result, fictitious elastic constants were determined from the two sets of diagrams as given in Figure 6. Overall, the tensile stiffness is extremely low with Young's moduli of approximately E = 5 kN/m for wales and course for the full stress interval. With E_{wales} = 10 kN/m and E_{course} = 26 kN/m it is only slightly higher for the stress interval 1 - 3 kN/m. In contrast, the Poisson's ratios are very high with minor ν = 0.83 and 0.66, respectively. Strains are large with up to 70 % under uniaxial loading. It can be stated that some of the calculated linear graphs do not correlate well with "their" measured stress-strain-paths.


Stress interval 0.1 – 3 kN/m

Stress interval 1 – 3 kN/m

Figure 6: Correlation between measured and calculated stress–strain paths and resulting stiffness parameters for Piquet Lacoste, NP 11, 55 tex for two stress intervals: 0.1-3 kN/m (left) and 1-3 kN/m (right) [© ELLF]

5 COMPUTATIONAL TOOLS FOR FORM FINDING, ANALYSIS AND MATERIAL SPECIFICATION OF HYBRID STRUCTURES

The interaction between the towers two form active systems – membrane and GFRP – determines the towers design and behaviour. A design process is required, which can predict this and feedback to the designer the resulting shape, but especially whether the material and elements specifications are sufficient. We use a two stage approach, combining a new developed particle spring simulation for an almost realtime form finding with hundred and more interacting bending members and a FE simulation for detailed analysis.

5.1 Formfinding

Established methods for the form finding of membranes, such as particle spring or dynamic relaxation, do not consider material properties or requirements from fabrication, such as patching [14]. During form finding the membrane is set to a fraction of its real stiffness in order to facilitate large deformations. The resultant shape represents the pure flow of forces. Our hybrid structural system consist however of interacting members, where, unlike the membrane, the rods maintain their bending stiffness during form finding and influence the final shape and stresses. The higher the curvature and the diameter of the rods, the higher the stresses in the material. The material of the rods need to have a high strength and a low Young’s modulus to be able to perform accordingly. It is important to create a curvature high enough to tension the membrane without risking breaking the rod under excessive bending. External loading, such as wind, causes quite big deflections of the structure, which exceeds easily the bearing capacity of the structure’s elements. Structural analysis is hence essential to design the tower within its bearing capacity.

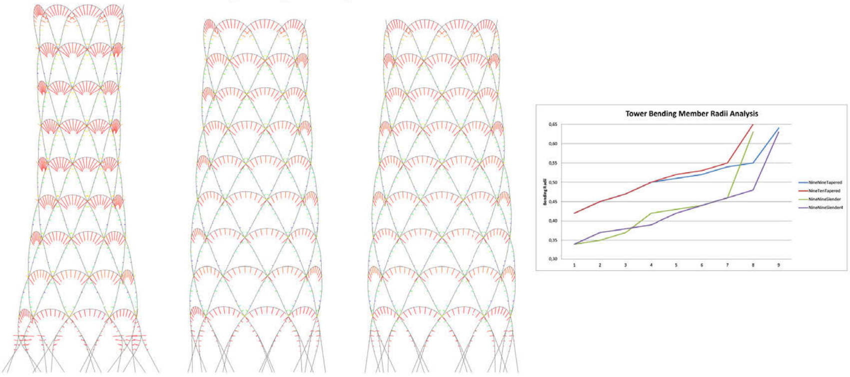


Figure 7: Formfinding tool in Rhino/Grasshopper with inbuild comparative bending radii analysis of differently dimensioned towers. Note the relationship between macro shape and bending radii.

The developed fomfinding tool is based on the Kangaroo 2 particle spring solver in Grasshopper/Rhino, operating on discrete piecewise linear geometries for modelling the behaviour of bending members and coupled discreet meshed for the tensile membranes in one unified and interactive system. The form finding and dimensioning process has three stages: generating, exercising, and refining constraints. The designer is guided during the process by inbuilt lightweight analysis features, providing feedback on the bending stress, utilisation and reserve of the member in isolation (Fig. 7), as the size and shape of the resulting membrane patches in the plane (Fig 8). Optimisation algorithms help to determine the best fit of the unrolled flat knitting patch in the max. width of the CNC knitting machine and constraints coded into the tool, prevent the design to exceed i.e. the max. length of bending elements. The process outputs the form found geometries and solver statistics.

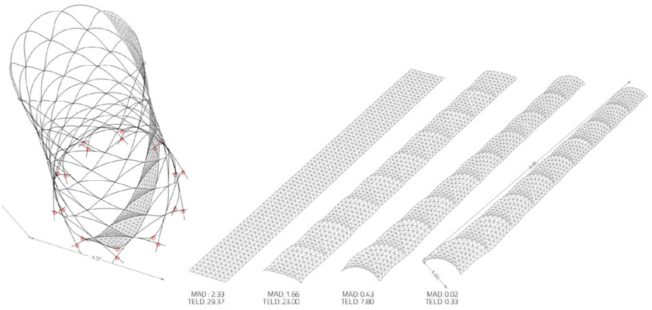


Fig. 8 Steps of refinement and deviations during development of strips of the doubly curved membrane into flat knit patterns.

5.2 FE Analysis

As the formfinding tool does not provide the resulting stresses, caused through the construction and external forces an FE environment (Sofistik) is used for subsequent analysis.

It is well suited to the real-time form finding and provides a precise mathematical definition of the global stiffness matrix. Large deformations must be simulated using an incremental process. Current approaches for the simulation of complex structural systems with large deformations, such as the *elastic cable approach*, developed by Julian Lienhard [15], reach their limit, in a system like the tower, where many elements and membranes are interacting. In our approach the form found geometry is imported as lines and surfaces into FE and converted into structural beam and membrane elements and materials, cross-sections and support conditions are defined. The results from the bi-axial tests defined the characteristics of the knitted membrane. The material behavior in terms of elasticity where nonlinear and linearised for two stress intervals to be used as elastic constants in the FE-simulation.

The expected levels of prestress in the hand assembled tower did only allow for the lower range of 0.1-3kN/m, so an isotropic Young's modulus of 10 Mpa was ascertained for the FE-simulation. The analysis confirmed the viability of the structural system, indicated however, that the membrane would have to be multiple times stiffer in order to balance the levels of applicable prestress, remaining structural capacity in the rods and external loading.

5.2 Preparation of Fabrication data

The specification for the different Knit patches is directly derived from the form finding tool. The form found patches are however curved and represent the knit in a pretensioned state. As this prohibits a direct unroll we develop the knit patterns in several steps:

1) The topology of the doubly curved patch is projected into the XY plane
2) A relaxation algorithm creates a best fit of the original length of the edges within the subdivided polygon to the flattened version. The numeric results showed overall

deviations in the range of millimeters. Extensive testing of the assembly of the derived cutting patterns onto physical models proofed the validity of the approach (Fig. 8). The pretension of the knit and the anisotrophy of the material is compensated through non-uniform scaling of the pattern. The necessary ratio is based on the bi-axial tests and measurements on a limited set of test patches and prototypes, which allowed determining the behaviour of the assembly rather than the constituting elements.

3) The compensated polygon representation of the unrolled stripes, are converted to vector representations and automatically refined with details, such as areas with reinforced textile (110tex), pockets, channels, holes and elements for the tensioning.

The refined vector pattern is non-uniform scaled to compensate the difference between the computational representation of a knitted loop for CNC knitting (square pixel) and the physical reality (rectangular).

6 CNC FABRICATION OF BESPOKE KNIT

The form finding tools provides finally the production information for the GFRP rods and for the CNC knit (fig 9). The information for the patches are bespoke to the level of local knit structure and overall shape.

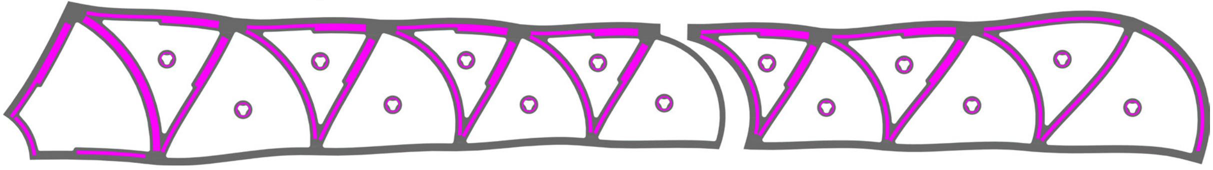
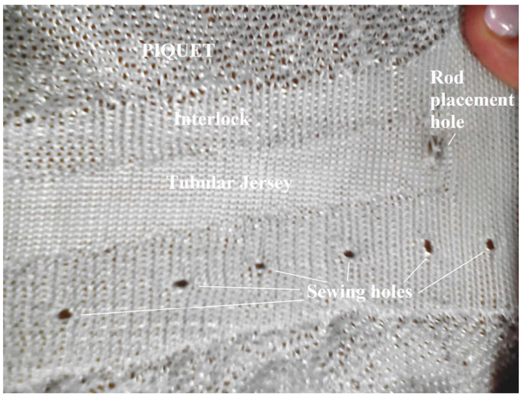


Fig. 9: Production information with all details included is generated in Pixel format. White= Piquet, Grey= interlock, Pink= Tubular Jersey. Red pixels = holes. The figure shows the state before compensation for knit and machine parameters.

Each patch has three **distinct knitting** structures. The central part, using Piquet, is more elastic, and transparent with greater aptitude towards stretching. The peripheral and other reinforced areas use Interlock structures and Tubular Jersey (Fig. 10).



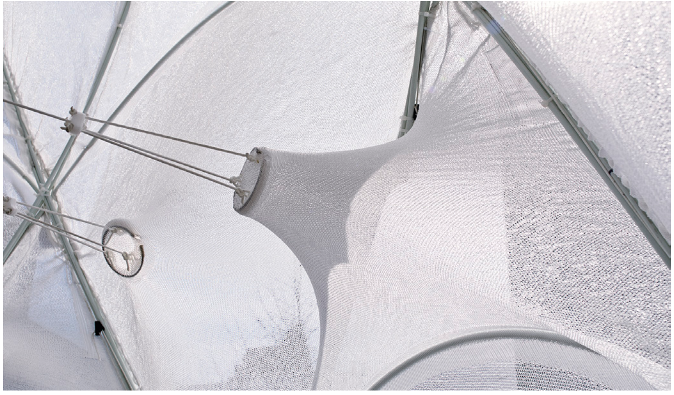


Fig. 10: Structural details on the textile. Piquet / Interlock / Tubular Jersey / Rod placement & sewing holes

Fig. 11: Each patch is reinforced in the centre and holds a detail for the tensioning to the towers centre axis. Three pairs of holes are allowing cables to pass from the outside to the inside without interfering with the membrane.

Both structures use front and rear needle beds simultaneously in order to increase the stability and functionality. Interlock produces perfectly intertwined double knit, while the shift to tubular jersey produces two independent faces, creating a pocket or cavity – the **channels and pockets** for the GFRP rods. The same principle is used for circular channels in the centre of the membrane patches, where steel rings are inserted, which provide in concert with CNC milled plastic details the interfaces to the towers inner tensioning system. Within the circles, three pairs of **Ajour knitting patterns create holes**, which allow tensioning cables to pass from the outside pulling plastic ring to the center of the tower (Fig 11).

This knitting technique is as well used in the boundary regions of the up to 8m long knitted strips and creates here holes for interfacing seems with neighbouring strips. These holes use only two needles width (line 2 of Figure 12), while a hole with four needles width (line 4) creates holes wide enough to introduce rods into the channels.

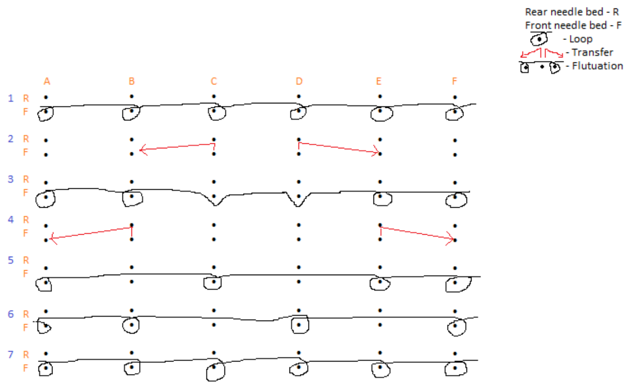


Fig. 12: Ajour Knitting Pattern is used in order to create a larger hole (approximately 4 needle width). Note that this representation is made on a Jersey basic structure in order to simplify the drawing. Here each line is represented by a pair of dots, each dot represents a needle and each line of dots represents a needle bed, rear and front, respectively.

Fg.13: Weft-knitting electronic machine Shima Seiki SSR112

The final production of the membrane took place on a weft-knitting machine Shima Seiki SSR112 (Figure 6), with 1150 mm of total width, 10 (needles/inch) gauge, 450 available needles and 55 take down. This machine was selected due to the high quality production, high memory capacity and a gauge similar to the one used during Fibrenamics´s developments, which should assure repeatability of the mechanical properties of the knit. Due to the complexity of the fabrics design and the elastic behaviour of the used yarns, the production speed was lower than for conventional textiles. Higher speed may lead to faults of the textiles structure, due to characteristics of flatbed knitting needles and as this would complicate the internal cutting system for the yarn.

It is challenging to CNC knit as bespoke and with the amount of changing detail, as in the tower :

- **The precise behaviour and dimension of knit is hard to foresee** before the actual production – despite all measurements. The channels should for instance all have the

same width in any angle on the surface. They should be tight enough to fix rods in the determined position, and wide enough for larger diameters of rods. Extensive tests were necessary.
- **Trade-off between the integration of detail and the stability of the structure.** This is especially true for areas around wider holes with *Ajour knitting pattern.* The sewing holes are made through transfer of loops between neighbouring needles (see Fig. XX Line 2, transferring C to B and D to E). However the placement holes couldn't simply be made by replication of this transfer, as this would compromise the structures stability. The increase in size of the hole was hence accomplished through creating a weakening of the surrounding structure. In this way the rest of the transfer could be introduced later, obtaining only a slightly larger but more elastic opening of the channel, so that rods could be forced in. Grinding the edges on the tip of the rods eased the insertion. Bigger diameter rods damaged however often loops and led to larger defects in the knit.
- **The inner logics of knit and fabrication limit the complexity in the structure.** Constraints emerge in the fabrication end, which make it difficult to realize the theoretically possible overlay of varied width of the knit, a varying amount of details and a stable structure. The special challenge in the pattern for the tower, was to place all crucial details into the knitting.
- **Knowledge, Process and Technological barriers.** In the production of knitted fabrics the synthesis of size, fabric's stability and experience and knowledge of technicians are decisive aspects. The needle bed determines i.e. the width of each part, whilst the achievable complexity, detailing and size is dependent on the storage capacity pattern without compromising texture and dimensional stability. Methods to untangle these constraints and create a more systematic and scientific approach are needed.

7 PROTOTYPING AND ASSEMBLY OF THE TOWER

The validity of the projects decisions were tested throughout the development process by means of physical models in increasing scale up to 1:1 prototypes. These models verified i.e. the precision of the formfinding tool through comparative studies of 3d scanned physical models and their simulation.

For the tower project the interaction of membrane and GFRP rods, the ability to pretension the knit through the rods manually, as well as the functionality of inserting and fixation of the rods in the textile through channels and pockets could only be verified in 1:1 scale prototypes. As CNC knitting on large scale machines means a considerable effort, the project had only limited possibilities to test and improve the taken decisions iteratively. The test of a single patch was possible prior to the actual production, verified the approach, but demonstrated as well, that the structure in total was more elastic and less precise than anticipated. Due to time constraints, the effective length of the rods was increased through sewing the pockets shorter. This led to imprecisions on the global scale and deviations from the simulated geometry. These were increased by further imprecision induced through the fabric connections of the rods. While the system of pockets and channels was generally strong enough to prevent rods from poking through the fabric, the design of the detail allowed for a torsion between the rods. A more fixed and precise solution would be necessary.

The final assembly took place on the ground, starting with the top layer, filling in each story underneath as soon as it was completed - a strategy, which made it possible to abstain from expensive temporary scaffolding. Simply a centered scissor lift was used to push the build part a level upwards. It turned however, out that hanging the structure created distortions, which could not be adjusted in this state. Having smaller more flexible jacks around the perimeter would be a better strategy, especially as the structure proved stable in intermediate states.

The monitoring of the tower over a four week period showed, that it was able to withstand wind forces up to 11 m/s.

8 CONCLUSION: POTENTIALS AND RECIPROCITY OF DEVELOPMENT AND DESIGN OF KNITTEDMEBRANES SURFACES (600 WORDS)

The project demonstrates the potentials of material specification in CNC knit for architectural structures. The project found several practical challenges in the process of specifying material properties in knit, their implementation into fabrication and the verification of these. These have been discussed in the chapters above. The project is first of all a case for a future integrated and interdisciplinary design practice, where a building structure can only be understood as an interacting multi-scalar system.

Feedback on tool and process level

The design of the towers hybrid structure required the integration of constraints, that determine the making of a single loop of knit, with those that operate on the largest scale. This is a call for an exchange and feedback between all partners from design to fabrication.

On the level of **design computation**, the projects demonstrates successfully, how feedback from all levels can be implemented in digital design tools and how these are the key component to design with highly interdependent hybrid systems. Information from the structural, fabrication and level of assembly was successfully integrated in the form finding tool and allowed to design the overall structure, as the discretisation of the surfaces, so that they stayed within the fabrication limits.

However, the tools need to be informed about the relations and properties of the interplaying components and materials and the processes to specify and fabricate them. The reciprocal nature of structures and processes was - and could - not be well understood in the beginning of the project. And while early design processes find usual a resort in “standard” material specifications, these assumptions are void, when design demands a high level of material behaviour and specification.

In the case of CNC knit this is obviously highly dependent on the **limitations of the actual CNC production in both size and data capacity, as the inner constraints of the knit structure**. These were not known early on in the tower project, which took hence resort in small-scale **prototypes** with placeholder materials. This approach did not scale well, as the material level is decisive for the hybrid structure. This is methodologically different to the geometric form finding of pure membrane structures, where small-scale physical models provide a sufficient point of departure. The developed **CNC knit structure** sufficed the determined requirements on sample size, with the exception of the material stretch. The shift to production level machines, the engagement with large knit structures with full details and the assembly on these within a bending active structure proved to be challenging. Earlier full-scale physical prototypes with the real materials would have enabled a better understanding of the physically achievable material and system behaviour.

The necessary approaches to **test and verify the bi-axial behaviour of the designed knit** and obtain a numeric base for simulation are currently experimental and time consuming and it has to be emphasized, that the obtained “fictitious” elastic constants are results of preliminary, but nevertheless quite practicable biaxial tests, which were modified for the knitted material in the first time. In future, the test and evaluation procedures have to be progressed in order to meet the requirements of the special knitted material. Furthermore, the constitutive law used for the determination of the “fictitious” elastic constants is actually limited to small strains which were not observed for the investigated knitted material.

The obtained values are sufficient to predict the overall structural capacity through **FE simulation**. The simulation is however sensitive and difficult to set-up to give a timely feedback to the design process. A coupling of the quick and stable form finding processes with particle based systems and precise FE analysis are hence necessary.

Feedback between disciplines

The project exemplifies the problem, that highly integrated projects with interdepended systems and scales pose. In the case of the tower design decisions were only possible in an interdisciplinary dialogue. An exchange of all partners was necessary at a point in time, when a design consists merely of ambitions and intentions - not requirements. This demands a designerly conversation between disciplines, which might not be used to the wicked and open-ended nature of design, the related symptoms of initial insecurity and the many loops and iterations, which are necessary to from the vagueness into a secure territory. Fast cycles between making, testing and specifying of material and structure are here an appropriate means to solidify the design and finally engage the potential, which resides within bespoke materials.

Potentials of CNC knit in hybrid structures

The benefits of CNC knit for The Tower were the integration of details into the knit. This allows to collapse the complexities from fabrication into the material itself. The activation of the material stretch allowed the knit furthermore to take on geometries, which would be difficult to achieve with patches made from weave. The elasticity of the material challenges however the construction and calculation of its behaviour. The knitted fabric shows in the conducted test, as in the final tower a non-linear behaviour, were a considerable stretch has to be introduced, before the knitted structure “locks” and is actually able to convey forces. This behaviour is different from the usual woven PVC coated membranes. It meant, that the stabilising pre-stress could only from the “locking” point onward be introduce into the membrane. As the geometry of the restraining system and the pre-stress in the membrane influence each other it was challenging to find their appropriate configuration in the pre-construction phases.

A better understanding of the actual forces in the tensioned areas would allow to enact on these with a better fitting choice of the diameter of the bending active element or even with local change of the knit structure. Such fabrication of membranes with graded material properties is another promising area of CNC knitting. It has only be touched upon in this project. We focused on the creation of reinforced zones in the membrane, a variation of knit structure offers even the potential to influence the membrane shape through locally stiffer textile material (Henrysson 2012). These processes require a complete understanding, control and coordination of the different processes in all disciplines.

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