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## Supporting research projects via student workshops

Max MARSCHALL\*, Michel SCHMECK, Christoph GENGNAGEL, Mette Ramsgaard THOMSEN<sup>a</sup>, Martin TAMKE<sup>a</sup>

\*Department for Structural Design and Technology  
Berlin University of the Arts (UdK)  
Hardenbergstraße 33, 10623 Berlin, GERMANY  
[max.marschall@icloud.com](mailto:max.marschall@icloud.com)

Centre for Information Technology and Architecture (CITA)  
Royal Danish Academy of Fine Arts (KADK)  
Philip de Langes Allé 10, 1435 Copenhagen, Denmark

### Abstract

As part of a joint research project between the Centre for Information Technology and Architecture (CITA) and the Department for Structural Design and Technology (KET), a one week student workshop was organised at the Royal Danish Academy of Fine Arts (KADK) in Copenhagen. This paper outlines the teaching methods applied to reach maximum insight from student interaction, despite the unfamiliarity the students had with the research matter: physical and numeric form-finding for light-weight hybrid structures. Hybrid structures are defined here as combining different components of low stiffness together to create an enhanced system of high stiffness.

**Keywords:** students, workshop, hybrid structures, computational design, form finding, bending active, bespoke, knit, finite element analysis.

### 1. Introduction

Within the scope of an ongoing interdisciplinary research collaboration program „Complex Modelling“ between the Centre for Information Technology and Architecture (CITA) at the Royal Academy of Arts Copenhagen (KADK) and KET, was a project titled „Hybrid Tower“ [1]. “Complex Modelling” explores new means of digital modelling that incorporate material performance into the feedback chain of architectural design processes. It incorporates the development of expanded computational tools, operating on parallel scales of design engagement and striving towards more informed workflows. The research project explored the possibilities of creating light-weight hybrid structures by combining bending-active [2] elastic glass fibre reinforced plastic (GFRP) rods and knitted fabric as a membrane [3]. The principle of dramatically increasing the load bearing capacity of GFRP rods through membrane restraint was to be demonstrated in a prototype of a rotationally symmetrical tower with a height of 8m. It was to be constructed by stacking overlapping rods embedded in a bespoke knitted membrane made from high tenacity yarn.

The project goal was to assess whether this structural system performs sufficiently and enables a continuous force flow between its discrete elements, avoiding the need for stiff joints between active bending members. An assumed potential was to add resilience using the structure's inherent flexibility. Compared to static and homogenous systems, this involves an increased level of complexity in terms of modelling, analysis, fabrication and construction.



Figure 1: Final prototype erected at Designmuseum Danmark

At UdK, a group of architecture students participating in a study course at KET were learning about membrane and shell structures. Part of the curriculum for this course was a workshop involving physical and digital modelling to further the students' knowledge on the subject. KET and CITA agreed to hold this workshop in Copenhagen and integrate it into the tower research project. The goal was to enable the students to learn effectively from a practical research project in the making, while at the same time contributing towards the project with their output and insight.

The project relied on numerical simulations using the particle based constraint solver from the beta version of the *Kangaroo Physics 2* plug-in for *Grasshopper* and was supported by FEM analysis in *Sofistik*. The digital tooling was adapted as the needs of the project shifted. It was therefore a challenging endeavour to organize a workshop that would produce new contributions by architecture students who had little experience with the structural design issues at hand as well as the methods of numerical form-finding.

## 2. Pre-workshop

Before the workshop, the project had been running for four months. The research team had put into place a workflow that would play an important role in how the student workshop was organized. They implemented new computational design models and feedback loops across different levels of scale and engagement, assuming that this would lead to enhanced, more creative and resilient building practices.

### 2.1 Macro Level

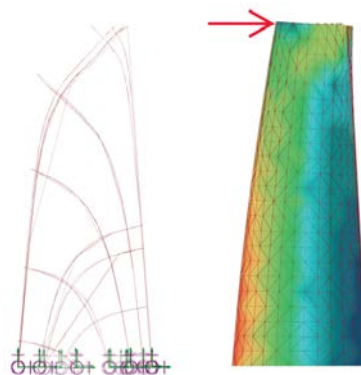


Figure 2: Structural analysis at macro scale

At macro level, the tower would behave similarly to a cantilevering hollow beam subject to wind loads, leading to crucial bending stresses at the base. This would need to be considered in the anchoring and detailing as well as the final shape design. The aim was to use the membrane to transfer the tension stresses resulting from the bending forces, while using the rods to bear the compressive forces. The analysis of the principal stress lines under wind conditions was the basis for conceptualizing the tower topography. Wind loads affect cylindrical tower sections with small compressive stresses on the side facing the wind, and large lateral suction forces on the other sides. This causes global buckling effects, with deflections increasing towards the tip. As a means of counteracting this effect, a tensile restraining system similar to that of a spoke wheel was to be applied to the interior to increase the radial stiffness. Cords were to be attached to the insides of membrane cells, spanning the tower cross section. Manual tests with physical mock-ups showed that this could provide horizontal stiffness and brace the rods that carry compressive forces.

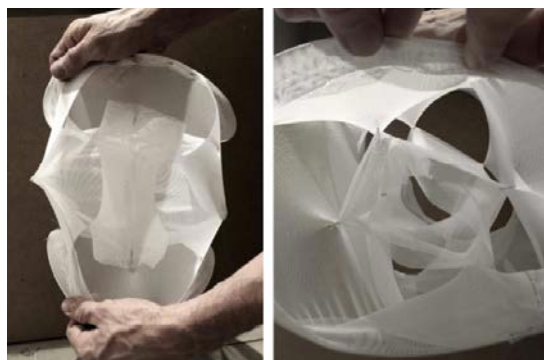


Figure 3: Early “spoke wheel” mockups

## 2.2 Meso Level

The main objective was to make use of the dramatic increase in load-bearing capacity of GFRP rods when restrained by a membrane. This concept needed to ensure that the rods' bending forces were transferred to normal forces. Meso level research therefore focused on developing a structural system using only actively bent elastic rods embedded in a bespoke knitted fabric. Special effort was put into developing the system as a modular and therefore scalable scheme, making it applicable to various shapes despite the limited available lengths of GFRP rods. Since the jointing was to be integrated into the knit, the rod connections would have to be linear in order to ensure the proper utilization of the membrane's load bearing capacity.

## 2.3 Micro Level

The micro level research dealt with the characteristics of the knitted fabric. The advantage of knitting compared to weaving is the possibility of integrating details for jointing and tensioning into the membrane itself. The aim was to embed the rods into the bespoke fabric via integrated pockets and tunnels, thus dramatically reducing the effort of subsequent sewing. Different knitting methods were analysed and compared with *Fibrenamics* at Universidade do Minho, A. Ferreira e Filhos, S.A., and the *Laboratory for Lightweight Structures* at University Duisburg-Essen [4]. The knit analysis was directly linked to the joint detailing at meso scale. Methods were investigated to minimize the need for pattern cutting and instead integrate form and details directly into the knitting process. A special challenge was to ensure feasibility during the construction process.

## 2.4 Feedback

So far, an intertwining feedback loop had been put into place linking experimental physical prototyping, simulation, 3D scans and architectural conceptualization. There was an active exchange of knowledge and ideas within the interdisciplinary group, consisting of structural engineers and

architects specializing on textiles and computational design. The loop would begin with conceptual discussions. Any thereby emerging ideas were initially tested in simple physical mock-ups. The insights taken from the physical prototyping process would result in design modifications that would affect the digital tooling responsible for the form-finding using *Kangaroo*. The results were further analysed with FE methods and fed back either into the *Grasshopper* definition, the physical prototyping or again into the conceptual discussion.

### 3. Numerical Shaping

Contrary to classical form-finding of membranes (which is independent of material properties and generates a pure equilibrium of force) form-finding of bending active hybrid structures requires the consideration of material stiffness. Both the axial and bending stiffness of the beam elements is taken into account, as well as the axial stiffness of the membrane. The relation between these types of stiffness is the driving factor of the form-finding process.

After an experimental phase of physical modelling, a topology was developed and implemented in the designer's software. Within the framework of this topology, a second series of experiments led to a wide range of geometries ready for evaluation. The tool used for the form-finding process utilized the *Grasshopper* plugin for the *Rhino 3D* CAD package to implement a “particle based constraint solver operating on discrete piecewise linear geometries for modelling the behaviour of bending members and tensile membranes in one unified and interactive system” [1].

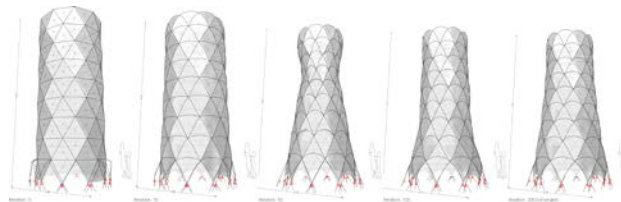


Figure 4: Iterations during form-finding process

The topological principle for design was the stacking of overlapping bending members around a central, vertical axis. The tool offered input parameters controlling the number of sides and floors as well as the distance between anchor points. This generated undiscretised bending members and membrane cells in the form of equilateral polylines. The cells were linked in groups that formed membrane patches spiralling upwards around the tower. These geometries were input into a separate process which created the discretised bending member polylines, the membrane patch meshes and the tension member lines. In order to simulate the detailing conditions in the later model, the bending members were extended to overlap with the respective rods of the floor underneath. The *Kangaroo 2* Physics system was used in its early development stage (called “Joey”) to iteratively solve the defined constraints, converging the model to a state of equilibrium.

The designer was able to influence the tower shape by manipulating parameter lists that defined the exact dimensions of the rods and the location of joints along the rod lengths.

### 4. Design Constraints

The method of operation had been effective in leading towards evermore informed models, and had resulted in the formulation of several boundary conditions:

- The pursued structure was an 8m-high tower-like pavilion with maximum width of 5m
- Rod connections needed to be linear in order to utilize the tensile load-bearing capacity of the membrane
- No third material was to be used; joints were to be integrated as pockets in the membrane
- The tower was to have openings at its base, making the interior accessible

The above-mentioned constraints presented the students with a set of unique design problems:

- ## 6.1 Group Work

In order to progress most efficiently, groups were formed and each assigned a specific aspect to work on:

- Numerical form-finding
- Physical prototyping
- Detailing and erection

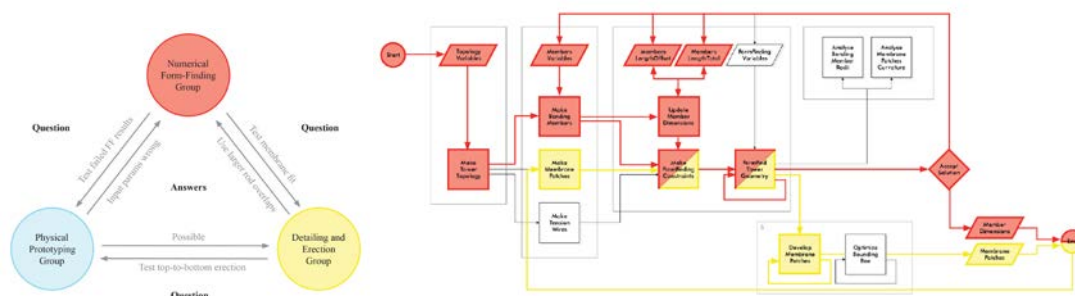


Figure 5: Example of group interaction

This concept created a fruitful workflow in which each team could concentrate on a single issue out of the complex design task. With the coordination by supervisors it was possible to exchange insights between the groups whenever a potential solution had to be tested for its practicality within the overlying process.

## **6.2 Reduction**

In order to further reduce the issue, sub-categories out of the research question were identified that were concise enough for the scope of the workshop, without losing their applicability in the research project.

For instance, the numerical form-finding pipeline used by the research fellows was initially reduced to the portions focussing on creating the bending members of the tower. The membrane as well as the tension members were at first not taken into account by the numerical form-finding group. This shortcoming, owing to the limited time frame of the workshop, could be mitigated to some extent since the research team was able to aid in making informed assumptions about the applicability of the chosen variations. For example, due to their preceding research, they could advise the students on how to produce variations with realistic bending member radii, thereby relieving the students from the time consumption involved in applying bending radii analysis. The detailing group was later able to apply part of the membrane generation portion of the form-finding pipeline to generate the membrane geometry for the highly reduced tower variations they were using to test their concepts for patterning and jointing. As a means of simplification, the membrane generation was not an iterative process but focused on solving specific variations.

Design parameters were tested one at a time. The numerical form-finding group was further divided into partner work, with each subgroup focussing on the effects of a single parameter on the overall structure. In later phases, the parameters leading to desirable outcomes were merged in order to combine the effects.

## **6.3 Experimentation vs. Iteration**

Apart from defining overall constraints and workflows, the students were initially left to experiment freely. The successful as well as the many failed results were documented and presented as equally valid additions to the general body of knowledge. Desirable properties resulting from the experimentation were identified early on, at which point the students were instructed to enter an iterative loop expanding on the possibilities of this one aspect. Once it had been explored to a satisfactory extent, work was continued in an experimental fashion. The concentrated work effort produced a multitude of solution proposals, out of which many – albeit speculative or unsubstantiated – contributed to a better understanding of the feasibility constraints. They also laid out the groundwork for a creatively more versatile array of potential strategies for future use after the workshop.

## **6.4 Consultation**

Key to the effective progression was the presence of consultants – professors, supervisors and research fellows – which enabled a quick feedback loop in the students' work. Similar to the way in which the research fellows had been working, the supervisors encouraged an exchange of knowledge between the groups, allowing them to see their respective ideas be implemented in a different scope of the project. The tight schedule forced all participants to channel their workload in an efficient manner. The experimental workflow was regularly extended by group reports, preliminary presentations and analysis by the supervisors.

## **7. Workshop Schedule**

- Introduction: Briefing on the status quo of the project and form-finding methods
- Group Work: Independent work on form-finding, prototyping, detailing and erection
- Discussion: Presentation of insights and decision on 1:1 scale prototype
- 1:1 Prototype: Construction of final prototype



## 8. Procedure

### 8.1 Numerical Form-Finding Group

At first, only bending members were taken into account to accelerate the form-finding process. Since a complete form-finding took several minutes to calculate, neither the membrane nor the tensile members were initially included.

This group was further split into subgroups, each analyzing the effect of a specific parameter on the overall form:

- Varying rod lengths per floor
- Varying position of connection points per floor
- Varying position of connection points per rod

It was observed that by changing these parameters it is possible for the designer to influence to some extent the shape of the tower. There is however not necessarily an intuitive correlation between the setting of the input parameters and the outcome; instead, an iterative experimental approach was taken to gradually achieve the desired effects.

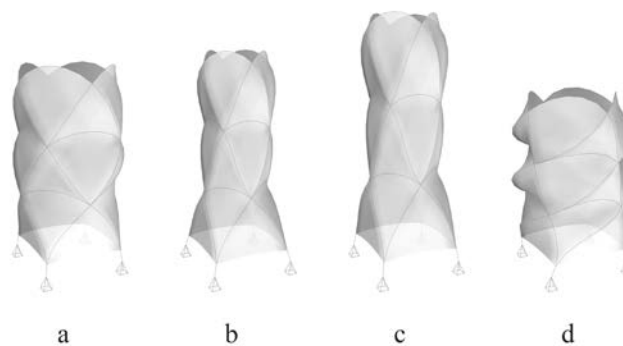


Figure 6: a) Reference shape. b) Shorter rods. c) Connection points symmetrically shifted towards rod mid points d) Asymmetrically shifted connection points.

Setting different rod lengths resulted in the most predictable results: the shorter the rods, the narrower the tower section becomes and vice versa. Varying the position of the connection points throughout the length of the rods is a more unpredictable intervention. While it is true that the membrane cells become increasingly slim while the connection points are moved to the middle point of the rods, the deflection of the rods from the initially cylindrical tower geometry occurred in a less expected manner, especially when using more complex configurations. The only way to achieve an asymmetric cell geometry was to vary the position of each of the two connection points on their respective rod.

Often the tool would produce disfigured results. Originally interpreting this as an error by the tool, the physical prototyping group was asked to build a mock-up using the selected parameters, only to find that the prototypes failed due to excessive bending in the rods. This suggested that seemingly false results produced by the tool may be indications of unfeasible input variables.

### 8.2 Physical Prototyping Group

During the course of the group work, this group built their prototypes at a scale of 1:4 in order to investigate a larger number of variations. Membrane patches were not taken into account, both for simplification and for comparability with the digital models.



To receive correct structural feedback from a scaled prototype, its stiffness has to be scaled. In the workshop, the 1:4 prototypes were built from GFRP rods with a 3mm diameter, while 8-12mm diameters were used in the 1:1 prototype. The 3mm rods were not scaled physically to match the correct properties. Despite this inaccuracy, the physical 1:4 prototypes were useful in gaining qualitative structural feedback:

- By manually applying forces, the principal behaviour under dynamic horizontal forces could be estimated qualitatively.
- 3D scans indicated that the gravitational displacement was likely negligible due to the minor dead loads of the slender GFRP rods. It furthermore demonstrated a high precision of the form-finding tool and feasibility during the assembly process.
- A reason underestimated so far for the small the deviations between the form-found models and the 1:4 prototypes was the fact that the digital tool did not take joint detailing into account. While the tool spatially blended bending members at their linear connections into a single strand, the reality was that joining two rods led to a diversion of centre lines.
- Another measured effect was the local displacement of rods along their predicted paths. Since jointing did without rigid connections and instead applied cable ties or membrane pockets, high stresses generally caused the connection points to twist slightly.
- Due to the lightness of the structure, it seemed likely that the tower could be built from top to bottom, subsequently placing the stacked upper floors upon the current, lower floor.

### **8.3 Detailing Group**

The goal for this group was to develop strategies to reduce pattern cutting and material usage, and create solutions for the integrated jointing of rods, applicable during the building process. The advantages of knitted fabric were to be explored experimentally regarding fabric performance, stress resilience and visual quality.

The intent of using CNC knitting for membrane production was to minimize the number of building components. At an early stage, it became clear that attaching the rods using only the membrane would be demanding. After a series of small experiments using woven textile and sewing machines, a 1:1 mock-up was fabricated that incorporated pockets and tunnels within the fabric. Various types of jointing were tested as well as combinations between different methods, increasing in complexity during the workshop.

In order to channel the students' efforts in a purposeful way, they were presented with subsets of planning issues derived from previous research. Joint detailing and connection methods for membrane patches (e.g. piano hinges, Jacob's ladder, zipper, etc.) were two separate issues. Another was the patch orientation, i.e. storey-wise patching or strips spiralling over the height of the tower. The assembly process was also initially handled as a separate matter, until finally all the above-mentioned aspects were considered regarding the overall feasibility.

This segmented workflow gave rise to a number of findings. In general, the students learned that the mechanical performance of the knit proved to be vastly different compared to typical structural membranes. The experiments confirmed that a desired geometric property in membrane design is high double curvature as this stabilizes the membrane. The openings in the membrane on the other hand disabled one of the project's main objectives: to create a continuous force flow between the structure's discrete elements. If the opening borders were not reinforced, the adjacent membrane patches would lose their prestress and wrinkle. Piano hinges were considered an advantageous method to join membrane patches since this alleviated the construction process. The importance of reinforcing the seam lines became apparent, as did the sliding of the rods within the joints. The joints posed the largest problem. Depending on the elasticity and amount of prestress of the membrane, the points of rod intersection would slide when lateral forces occurred. To increase the rigidity of the joint, additional fixation was suggested, such as cable ties or 3D printed connectors. The intended manual

construction allowed only for low prestresses to be realized, resulting in a malleable structure subject to large deformations and displacements between its building components. Horizontally oriented patching was identified as the optimal solution for the intended top-to-bottom construction method.

## 9. 1:1 Prototype

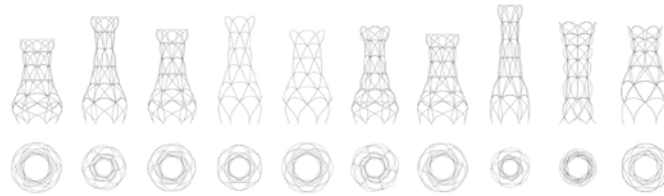


Figure 7: Digital variations produced by form-finding group

The sum of variations produced by the numerical form-finding group was compared, leading to a last round of iteration. This produced a range of bulbous, vase-like shapes that varied mainly in one characteristic: symmetry of the individual membrane cells. Although asymmetry was considered aesthetically more appealing, a 1:4 mock-up revealed that these variations caused excessive bending forces, rendering them unfeasible. Since the high compressive stresses at the base of the tower were best counteracted by vertical, symmetrically oriented rods, the group agreed to go with a mirror-symmetric variation.

Construction of the 1:1 tower proceeded successfully, as planned without any scaffolding and from top to bottom. It was however built indoors and without its membrane. Since the outwardly leaning legs were bent strongly even under dead loads, a more hyperbolic shape with a direct load path was recommended for the final tower.

Apart from displaying a slightly larger displacement under its dead load condition, the 1:1 prototype differed only slightly in shape to that in 1:4 scale. It was however observed that the large prototype was much less rigid and exhibited large deformations under external loads. This deviation was expected, since the rod diameters were not physically scaled and less rigid relative to their sizes. The joints were implemented using cable ties, which slid easily on the smooth surfaces of the rods, causing some of the joints to shift. It was suspected that this would cause major problems in the final prototype, when facing real weather conditions.

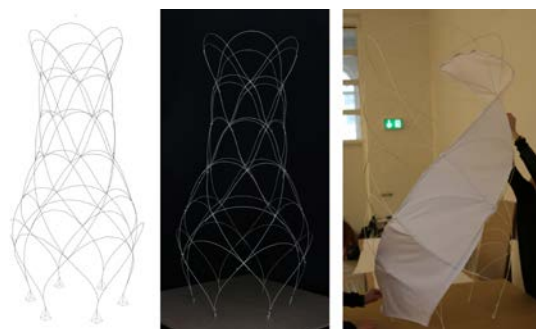


Figure 8: From left to right: digital model, 1:4 physical prototype, 1:4 membrane patch

## 10. Conclusion

After the workshop in February 2015, the research project proceeded to the realization phase and the team exhibited their final tower prototype at Designmuseum Danmark [5]. The following properties of this prototype derived either directly from the workshop or through discussions sparked by the result of the workshop:

- The top-to-bottom erection method could be directly applied to the final construction and proved to be a simple and effective procedure for the manual assembly.
- Details were based on the workshop's testing of their structural ramifications and feasibility during the erection process. The analysis of the effect of the flexible joints played an important role in the further development. Since the digital tool did not consider this, the physical prototyping proved to be essential.
- A variation with symmetric mesh cells was chosen, since this had been proven to be a more feasible solution and to perform better structurally.

The workshop also produced a number of more implicit findings. Generally, the participants' understanding of differences between digital models and physical prototypes of complex hybrid systems improved, and the importance of integrating physical prototyping into the research process was confirmed. The prototypes were essential in developing erection methods and jointing concepts. They allowed both the students and the research team to rapidly gain an understanding of the structural performance and feasibility of the tower as well as the parameters influencing it. It enabled the team to make more informed design decisions, creating a more efficient and target-oriented research progress. By approaching the design issue with different methods and on different levels of scale, a high influx of knowledge could be achieved. This was increased by the sheer amount of variations produced, which was facilitated by the intense student workshop.

The group work concept proved to be effective in generating a surprising influx of knowledge in a limited time frame. Although this knowledge substantiated itself less in new insights and more in the detection of potential risks and weaknesses of the structural system, it did produce a list of issues that formed the groundwork for an ongoing discussion in the research team and shaped the further project development.

A central aspect of the workflow during the workshop was an experimental approach. Considering the students' lack of knowledge on the subject, this proved to be the method most likely to harness their capabilities. A much larger time frame and effort would have been necessary to involve them profoundly in the project development. This way, the project could be furthered in a way that produced quick, tangible results beneficial to the research team as well as to the students' increase in knowledge. The physical mock-ups gave a surprisingly accurate qualitative impression of structural implications and helped determine which factors may be negligible and which crucial.

The workshop was organized at a stage of the research project where many aspects of the final design had not yet been agreed upon. This gave room to explore a vast number of possibilities, creating a catalog of ideas for the research fellows to reflect upon in the subsequent research.

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