# 35 Computational form-finding of fabric formworks: an overview and discussion

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It is well known that the shape of a structure determines its mechanical behaviour and that this principle of 'form follows force' can be used to structurally inform architectural design. Taken to its extreme, the result is a form-active structure that is shaped so that under load no bending exists, only axial or in-plane compression and/or tension stresses. Examples of such structures are shells, cable-net or tensioned membrane roofs and tensegrity. The shape of form-active structures is not known in advance and requires a process called form finding or shape finding. Flexible fabric formworks present a new application for form finding with the distinction of being a construction method rather than a structural typology. Existing form finding applications have yielded over half a century of research into computational form finding methods. This paper will discuss how form finding can be applied and adapted to the design of fabric formworks and what aspects come into play. Early implementations of fabric formwork design tools will be shown to demonstrate the possibilities of computer design for this building technology and presented as the basis for further discussion.

## 1 Introduction

Fabric formwork technology, and the concept of using fabrics or membranes as the main material for concrete moulds, has a long history in architecture and several fields of engineering (Veenendaal *et al*., 2011). However, one cannot speak of any significant tradition in the building industry as a whole, as examples of commercial projects remain rare. One obstacle in using fabric formworks is perhaps the care necessary in designing such a formwork. Whereas traditional rigid formworks are seen as a technicality that the contractor can deal with, a fabric formwork and how it is designed will influence the resulting shape. Understanding of this construction method is therefore a necessity during early design stages. The development of accessible tools for the design and analysis of fabric formworks may be one prerequisite to unlock the full potential of fabric-formed structures.

An important analogue to the design of fabric formworks is that of tension structures, such as cable-net roofs and tensioned fabric roofs. In these cases, an engineering tradition exists in which both physical and numerical modelling is commonly used at early design stages. Predicting the shape of the fabric as a result of the boundary conditions has been called form finding. This paper discusses existing uses of physical and digital modelling of fabric formworks, mostly from academic literature, presenting an overview of this specific topic. Then, examples are given of a simple, custom 2D form finding tool as well as an early 3D implementation of a more general design tool. The results are used as the basis for further discussion on future work, before drawing some conclusions.

## 2 Physical form finding

The current practice of designing new fabric formworks is done on the basis of physical models, ranging from scaled to even full-scale mock-ups, or is directly carried out from concept to on-site fabrication. The Centre for Architectural Structures and Technology (C.A.S.T., 2008) in Winnipeg, Canada, in particular has a large facility for the production of physical models. Based on 15 years worth of experience, the director, Prof. Mark West believes that "whatever can be built in scaled, working models can be constructed at full-scale." This is echoed by Anne-Mette Manelius at the Royal Danish Academy of Fine Arts in Kopenhagen, Denmark, who, based on several large student workshops, says that the relation between scaled and full-scale models is "quite direct". Both comments correspond with the fact that form finding - finding shapes in static equilibrium - can mathematically be considered as a purely geometric problem. They rely on four types of physical models:

1) Small-scale (1:10, 1:5, sometimes even 1:3) models using nylon fabrics and (spray) plaster;

2) Small-scale models using sand;

3) Full-scale models using watertight membranes and water, limited to modelling of filled fabric formworks, and

4) Full-scale models using (mostly) geotextile woven fabrics and (reinforced) concrete.

Reasons for building full-scale models are (a) to clearly demonstrate feasibility and (b) to work out economic and simple construction strategies. Furthermore, complex and untailored formworks will result in folding and wrinkling of the fabric. This is challenging to model either through scaled models or digital models, and (c) full-scale prototypes are obviously better predictors for the on-site construction and the final shape. Another reason for full-scale models is (d) the tradition in engineering academia to verify theoretical models through physical testing. Load testing of full-scale models of fabric formed beams and trusses has taken place at C.A.S.T. (publication pending), the University of Edinburgh (Lee, 2010) and the University of Bath (Garbett, 2006 and Orr, *et al*., 2010).

Some recent Master theses with an emphasis on physical modelling are by Suzumori (2006), who combined 3D-printed scale models and full scale mock-ups for the design of fabric formed sound barriers, and Mohapatra (2011), who used small scale plaster models to explore different fabric formed structural elements, before focusing on a column supported vault. An idealized version of the physical models' result was analyzed in a finite element program (ANSYS).

## 3 Computational modelling

Despite a large body of work in the form finding, design and analysis of prestressed fabric structures, application of these methods to fabric formwork design has only recently taken place. Existing examples are from the past decade, most of them in the latter five years. This section presents an overview of previous work. Though many of the following references are Master theses and student projects, some first instances of postgraduate or professional work in digital modelling can be found.

### 3.1 Wall panels

The first example concerns the structural optimization of fabric-formed wall panels (Schmitz, 2004). A manual, iterative procedure was developed to achieve an optimum structural shape for a panel based on its support conditions. The panel was analyzed in a finite element program (ADINA) and checked for strength requirements based on the load case.

### 3.2 Beams

Several theses at the University of Bath, UK, considered the case of fabric-formed beams (Figure 1) modelled as a series of hydrostatically loaded finite strips, an approach called hydrostatic form finding. The hydrostatic shape taken by such a strip is analogous to the elastica first solved by Euler (Wikipedia, 2012). Initially though, a more practical, empirical formula was derived based on loading strips of fabric with a viscous liquid (Bailiss, 2006) and was later refined (Garbett, 2008). These results were later compared with a numerical procedure based on the analytical elastica (Foster, 2010). "The beam [..] modelled as a number of [..] sections [..] only allows for curvature in the transverse plane to be considered." However, their work assumes that "a sufficiently large number of sections can adequately compensate for longitudinal variations in profile" (Foster, 2010).

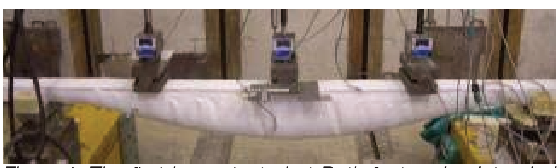

*Figure 1: The first beam tested at Bath featured unintended wrinkles due to the stiffness of the fabric (Bailiss, 2006), but subsequent beams corresponded well with their design.*

The first author has applied the form finding method of dynamic relaxation to fabric-formed beams. The resulting shapes were fed into a finite element program (ANSYS) to check the performance of these concrete beams. Using a genetic algorithm, new boundary conditions were automatically created as the entire procedure would then attempt to evolve towards more optimal beam shapes (Veenendaal, 2008; Veenendaal, Coenders, Vambersky and West, 2011).

### 3.3 Shells

Several studies were performed at the Vrije Universiteit Brussel, Belgium, on the modelling and shaping of columns and particularly shells. A software program for the design and analysis of tensile structures was used (EASY). Scaled mock-ups were made for verification including a non-prismatic column and a saddle-shape shell structure (Cauberg, Parmentier, Vanneste and Mollaert, 2009, Guldentops and Mollaert, 2010). They report “deviations between 5 and 58 %, on a calculated deformation of [the shell] about 15 mm for a span of 2 meter”. These deviations were attributed to slipping at the fabric edges and dynamic effects of shotcreting (Figure 2) and might also be the result of possible inaccuracy of the numerical cable-net modelling of the membrane.

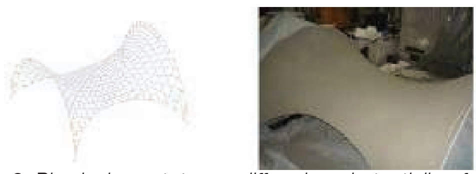

*Figure 2: Physical prototype differed substantially from numerical model (Cauberg, 2009).*

A novel form-finding strategy was developed by the second author for similar saddle-shape shell structures, based on the force density method and a nonlinear least squares method. The procedure calculates the prestressing required in a fabric formwork to approximate a given target shape for a fabric-formed shell. (Van Mele and Block, 2011).

Zwarts & Jansma Architects, Amsterdam, Netherlands and Zaha Hadid Architects, London, UK in cooperation with the AA Visiting School have both recently designed cable-net and fabric formed thin-shell structures. Zwarts & Jansma Architects designed two large-span structures. They used plaster and rubber as well as wire models before applying digital form finding using both custom written Visual Basic components and Kangaroo for Grasshopper (Torsing, Bakker, Jansma and Veenendaal, 2012). Finite element analysis (SCIA Engineer) was carried out by structural engineering firm Iv-Groep. The AA Visiting School in Bangalore and the Zaha Hadid Computation and Design Group have designed a fabric-formed shell pavilion. They used custom C++ code with Maya’s API for interactive form-finding that uses a simplified Euler and Mid-Point integration method for a particle spring system, and Maya Nucleus, which uses implicit integration, for final form-finding before carrying out structural analysis (Algor, now Autodesk Simulation) (Bhooshan and El Sayed, 2012).

### 3.4 Structural systems

Apparent in architectural research is the interest in casting entire freeform structures in fabric formworks. This is evident in multiple, recent student projects and Master theses.

The FattyShell project at the University of Michigan, by Kyle Sturgeon, Chris Holzwart and Kelly Raczkowski (Dezeen, 2010), involved three stages in its digital design workflow. A custom Rhinoscript, based on Lindenmayer-, or L-systems, was used to design the overall lay-out of the structure. It generated primitives relative to the site context in the form of a low polygon mesh. This surface mesh was minimized using 3DS Max’s Relax function and was subsequently unfolded to 2D patterns using Pepakura Designer. Note that the final concrete filled double-layer membrane was digitally modelled as a minimal surface (Figure 3).

*Figure 3: FattyShell project (Dezeen, 2010) was modeled as a surface with concrete inflation not taken into account.*

The DigitalPlaster project at the AA School of Architecture, London, UK (DigitalPlaster, 2012), featured a five-stage digital workflow. The overall organization of the structure was generated in Processing using a particle system and Verlet integration. The stresses in the structure were then analyzed in Algor, and served as input for the patterning and local density of pressure points in the formwork

(Rhino + Grasshopper). Maya Nucleus was then used for materialization and inflation of the fabric (also for 3D printed models), before unrolling the surface and generating patterns in Rhino. Physical models were made from nylon and plaster and also 3D printed (Figure 4). Differences occurred near the supports, possibly due to modelling of the fluid pressure as a constant rather than hydrostatic pressure. Note that the plaster model did not feature the intricate facades present in the 3D printed model.

*Figure 4: DigitalPlaster project (DigitalPlaster, 2012) shows differences between plaster model (left) and 3D printed model (right).*

Another recent student project at the Southern California Institute of Architecture (Emery, *et al*., 2011), used Maya Nucleus as well for form finding of a concrete filled structure. Differences between design and result were explained by the excessive stitching necessary near the legs (Emery, 2011) and bulging (Figure 5) is likely due to incorrect material modelling and/or patterning.

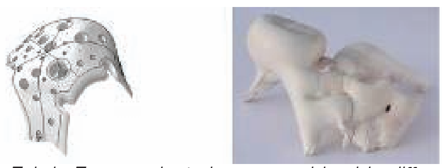

*Figure 5: Fabric Form project shows considerable difference between digital model and latex and plaster model (Emery,* et al*., 2011).*

## 4 Developing a digital design tool

From the existing examples in Section 3, it is clear that digital modelling can be used to perform three main design tasks: form finding, structural analysis and patterning.

The benefits of using digital models in the design of fabric formworks are:

1) Replacing full-scale models, and time, effort and space associated with them;
2) Allowing for large-scale models, not feasible with physical models (e.g. large-span roofs and bridges), and
3) Creating digital information, vital for communication, drawings and numerical analysis.

### 4.1 Design scenarios

In order to develop a flexible design tool, an inventory should be made of possible scenarios in which such a tool is used.

Fabric formworks are generally (pre-)stressed through a combination of mechanical prestress of the fabric (in-plane), concrete fluid pressure (normal-to-plane) and air pressure (normal-to-plane). The designer applies these to a surface, possibly prescribing a prestress, a reference height for the concrete pressure and/or air pressure.

Apart from these methods of prestress, the designer manipulates the boundary conditions of the fabric. In other words, he or she decides at which locations the fabric is supported and in what directions these supports are fixed.

The following problems could then arise, each of which needs a distinct numerical approach to solve:

1) The initial geometry of the fabric and its stiffness is given, and the designer wishes to determine the final, resulting shape from elastic deformation (analogous to procedures in structural analysis).
2) The target geometry is given, and the designer wishes to find the closest-fit solution possible with a fabric formwork (similar to previous work (Van Mele and Block, 2011)).
3) The maximum amount of volume (concrete) and/or surface (surface) is given, and the designer wishes to find the minimal surface subject to these constraints (analogous to procedures in form finding of pneumatic structures).

### 4.2 Applying form finding to fabric formworks

To create a digital form finding tool, existing form finding methods have to be adapted. Key aspects, which differ from conventional applications of form finding, are:

1) Concrete pressure, where we can note that (a) it is analogous to pneumatic structures in the sense that it acts normal to the fabric surface and (b) it can be modelled as hydrostatic, but it is understood that hardening of the concrete influences the pressure and thus the shape, depending on the speed and method of casting.
2) In membrane structures the surface is normally designed to create an as uniform stress state as possible and avoid any wrinkling. In fabric formworks avoiding wrinkling is only a structural requirement when the surface describes a compression-only shell to be cast. In general however, one could allow for wrinkles and maximize the use of large, flat sheets of fabrics, as is often the case at projects at C.A.S.T., or indeed apply tailored solutions with cutting patterns which is of current interest at the University of Edinburgh.
3) It is also common to manipulate the formwork normal to the plane of the fabric, by either pushing or pulling the fabric from the inside or the outside. This creates an unusual type of support condition (though also found in double-layer air-inflated structures).

### 4.3 Approach

The overall objective of the authors' research is to develop numerical approaches that perform the tasks of form finding, analysis and patterning, solve the design scenarios in Section 4.1 and account for particular aspects in Section 4.2, and implement these in a computational framework. The framework is written independently in Python, which can then be connected to any type of GUI. To avoid sequential design steps with feedback loops, and to avoid any black-box solving, emphasis is placed on (ideally real-time) interactivity of the interface, integration of the design steps and intuitive, visual feedback of the impact of design choices, mostly in terms of geometry and forces of the fabric. Some early results are given in the following sections.

## 5 2D example

A parametric design tool was developed to aid in the design of the formworks for a series of columns (and benches). The columns are part of a canopy in front of the new Women and Newborn Hospital in Winnipeg, Canada (Figure 6).

### 5.1 Women and Newborn Hospital canopy

Construction on the new hospital started in 2011. The award-winning design by Smith Carter Architects features an entrance designed as a welcoming and accessible front door. For the entrance canopy and a series of benches, C.A.S.T. has been approached to design fabric formworks for the canopy slab and supporting columns as well as the benches.

*Figure 6: Entrance of the Women and Newborn Hospital, with a fabric-formed canopy (right).*

According to Prof. West, "finding the geometry using physical modelling was very time consuming, and was done through multiple full-scale water tests". For structural calculations, the columns are being modelled as simplified, prismatic elements. This of course leads to some redundancy.

Despite having found a final shape, constructed a mould and simplifying the structural calculations, the structural engineer nonetheless required digital sections of the columns. Deriving these sections from the physical models is not straightforward. For this reason digital tools were needed.

For a constant girth (the standard width of the fabric) and a fixed breadth at the top (dictated by the design of the falsework), the tool has to calculate the structural depth of the section and generate the geometry for submission to the structural engineers (Figure 7).


*Figure 7: Chalk sketch at C.A.S.T. explaining the design problem*

## 5.2 Section Finder

Initially, the team at C.A.S.T. used an Excel sheet from the University of Bath, based on the elastic mentioned in Section 3.2. Though accurate, the spreadsheet did not allow the quick generation of multiple sections along the column. Two parametric models were then developed by the authors in Grasshopper, one based on the elastica, one using dynamic relaxation (Figure 8) (Barnes, 1999). The former was based on the Excel sheet (requiring goal-seeking for each new set of input values) and served to verify the results of the latter model (a more interactive model based on elastica is possible if the goal-seeking required at each step were automated). The latter model was then further developed and sent to C.A.S.T. for use in the project.

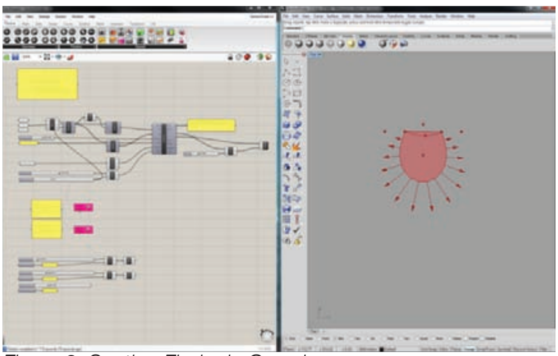

*Figure 8: Section Finder in Grasshopper*

The model allows input of (a) the two support points with, if necessary, a fixed horizontal distance between them, (b) an initial length/girth of the fabric and (c) membrane stiffness, and (d) the reference level for the concrete fluid pressure. Varying any of these points or parameters, one instantly obtains different possible sections (Figure 9).

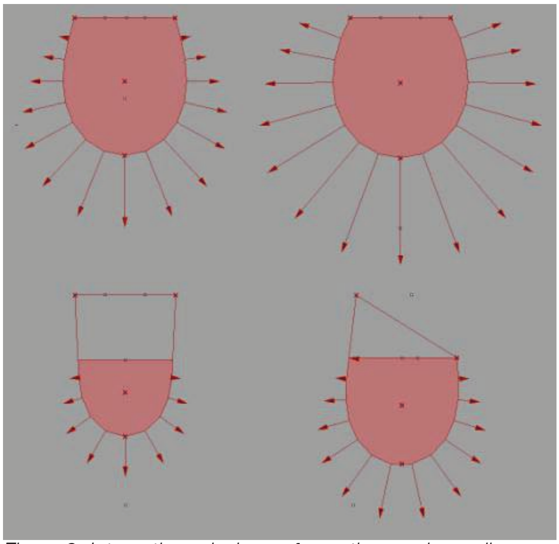

*Figure 9: Interactive design of sections, depending on concrete level, supports and fabric length.*

In addition, target values can be entered for (e) the final length/girth of the fabric, or (f) the maximum structural depth of the section. The user can then optimize for either of the two target values, in this case using Grasshopper's Galapagos solver (genetic algorithm). This was of primary interest for the project, and comparisons to results obtained from physical plaster models from C.A.S.T. show agreement. Differences visible in Figure 10 seem to be related to slight asymmetry in the physical model.

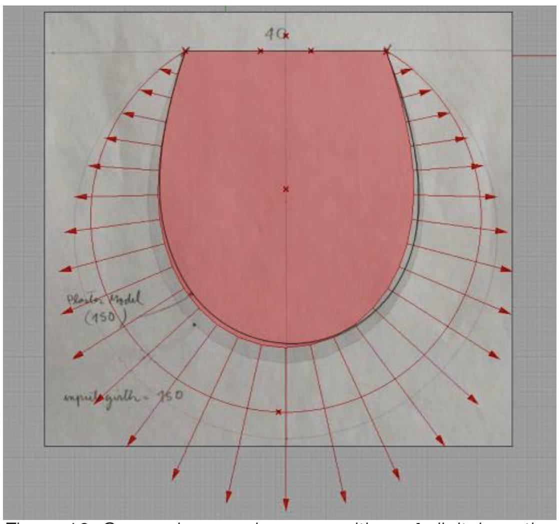


*Figure 10: Comparison and superposition of digital section and plaster model from C.A.S.T.*

### 5.3 Results

The parametric tool, developed to generate sections of a concrete filled fabric formwork, was successfully implemented in the ongoing work at C.A.S.T. for the Woman and Newborn Hospital. The project itself demonstrated the difficulty of modelling and predicting non-prismatic elements. The physical modelling of the curved fabric-formed benches was more involved than the straight columns for which the tool was made. This explains the challenge of 3D modelling observed in previous examples referenced in Section 3.4. The use of 2D modelling for elements with variable section is practical within limits, as demonstrated by its use for optimized beams in the work at the University of Bath (Section 3.2).

## 6 3D example

Another design tool for three-dimensional formworks is being developed by the authors. The tool is written in Python, and connected to Rhino 5.0 through a set of toolbar buttons. Two examples from the tool are used here to discuss the three key differences with conventional form finding, and how they can be dealt with.

The application of concrete pressures is straightforward. The pressure P itself is calculated from the density of the fluid concrete ρ [kg/m$^3$], the gravitational constant g=9.81 N/kg and the vertical distance h from the reference level z0-z [m]:

$$P = \rho g h = \rho g\left(z_0 - z\right) \tag{1}$$

At each iteration, for each node, the tributary area A [m$^2$] (surface area subject to this pressure) and the unit normal vector n (direction of the pressure) are recalculated to then compute the force vector F [N] on the node:

$$F = AP\hat{n} \tag{2}$$

To find a shape, a combination of an elastic stiffness matrix method (Tabarrok and Qin, 1992) and the natural force density method (Pauletti and Pimenta, 2008) was used for form finding. Both methods are formulated using simple, constant stress triangle (CST) elements. The former was used to introduce elastic deformation (the latter is a purely geometric method) and the latter was chosen to derive a stiffness matrix in such a way that each iteration is in static equilibrium and presents a viable configuration. Figure 11 shows a result from a square initial geometry subjected to fluid pressure with a low fabric stiffness. Note the stress concentrations in the corners, particularly at the top.

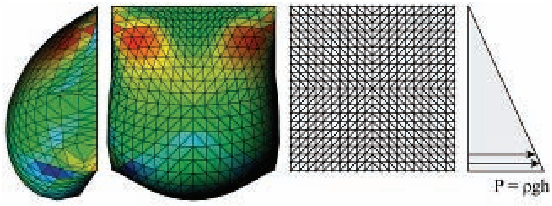


*Figure 11: Deformed, final geometry (left), initial geometry (middle) subject to initial concrete pressure P (right).*

In the corners, and depending on the fabric stiffness, wrinkling of the fabric can be expected as the square initial needs to deform to the double-curved final shape. Normally, this would lead to divergent behaviour in the numerical simulation (Figure 12, right). This is because compressive stresses occur, with which the CST elements, that have no bending behaviour, cannot cope in a physically meaningful way. Wrinkling conditions from Tabarrok and Qin (1992) were introduced leading to stable solutions:

If wrinkling occurs, then the appropriate stresses are set to zero, and small values are introduced for local stiffness. It is interesting to note that nomenclature from C.A.S.T. describing induced wrinkles and folds as either ‘push-buckles’ or ‘pull-buckles’ correspond to bi- and uni-axial wrinkling of the fabric.

The calculation of the principal stresses from an arbitrarily oriented stress vector (omitted in Tabarrok and Qin (1992)) is:

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}} \tag{3}$$

Introducing these conditions leads to stable solutions, as shown in Figure 12 (left).

However, wrinkling is not clearly visible due to the coarse mesh and the lack of bending/buckling behaviour of the elements. It is therefore easy to identify zones where wrinkling occurs, but difficult to actually show individual wrinkles, as this requires finer meshes and/or more accurate element types as well as additional material modelling. This slows down the computations and presents a challenge to the idea of an interactive design tool, if visually accurate wrinkling is of importance for the design.

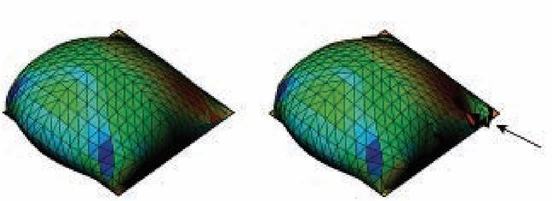

*Figure 12: Result including wrinkling behaviour (left) and without (right), showing divergent behaviour.*

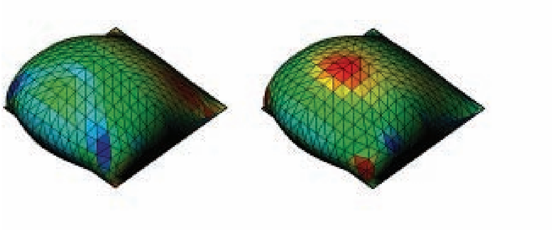

*Figure 13: Stresses in the final state as a result from form-finding from an initial flat, square net (left) or from a finely patterned net (right)*

Another aspect is that of patterning and also how this influences the stresses within the fabric. If the initial fabric is not the square geometry in Figure 11, but one that closely follows the final double-curved geometry with a higher fabric stiffness, different stresses are obtained. Figure 13 shows that the stresses are distributed differently when the geometry is patterned (based on the final geometry). The range of stresses and strains decreases as well, allowing more efficient use of the chosen fabric. The trade-off is the increased complexity of the formwork, now requiring tailoring.

Methods of patterning can be taken from practice in tensioned membrane structures. Typical approaches rely on geodesic lines along the surface to produce straight patterns while using the maximum width of typical fabric production rolls. Figure 14 shows one possibility for this example. Designing these patterns is another challenge. In particular, once the patterns have been chosen and flattened, the local stresses in the fabric will determine the compensation along the pattern edges. Furthermore, fabric formworks can have very complex shapes, which might not be as straightforward to subdivide as typically more symmetrical tensioned membrane and pneumatic structures.

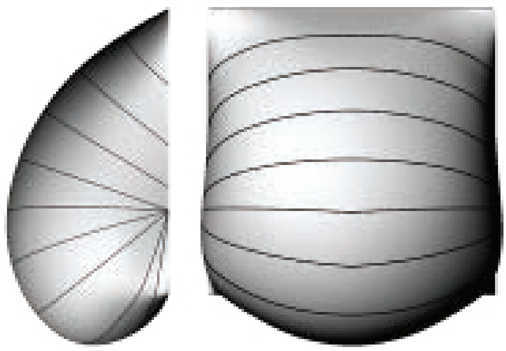

*Figure 14: Possible patterns of the final geometry based on geodesic lines between points along the boundaries.*

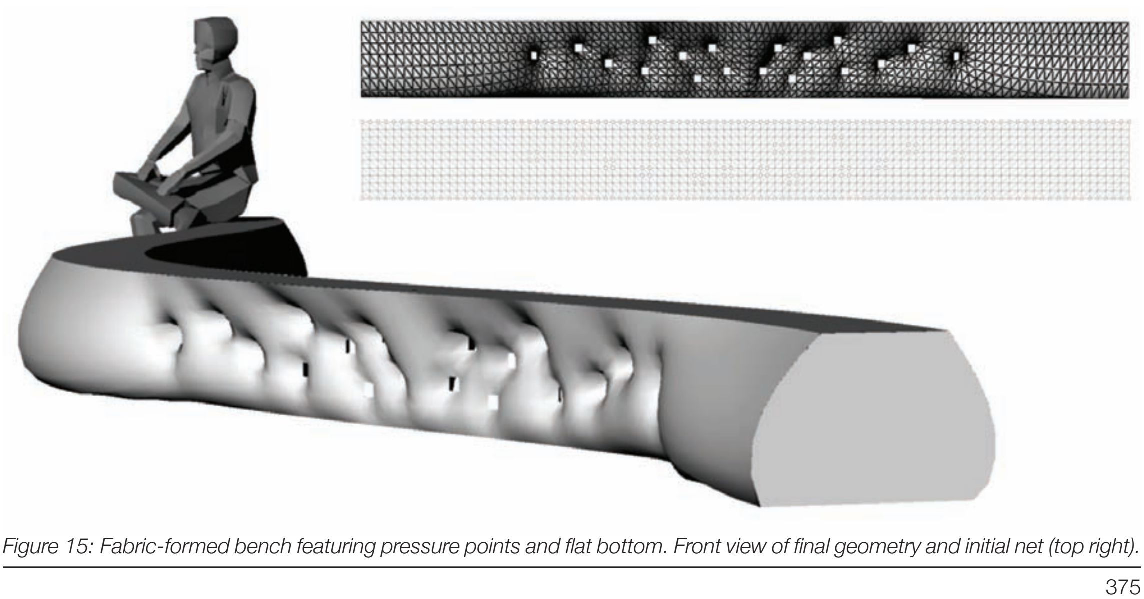

*Figure 15: Fabric-formed bench featuring pressure points and flat bottom. Front view of final geometry and initial net (top right).*

The final key difference in Section 4.2 is that of in-plane support conditions. Figure 15 shows a curved fabric-formed bench with in-plane supports, achieved through fixed supports point (the small pressure points or impacto's) or contact analysis with a boundary (the plane on the bottom of the bench).

These examples show that in principle each key difference can be solved. Future work will focus on improved numerical methods and interactivity.

## 7 Discussion

Based on literature, correspondence with others in the field of fabric formworks and our own investigations, two topics are discussed on the role of computational design in this case.

### 7.1 Physical versus digital modelling

The use of physical modelling offers many benefits. It provides tangible proof of what can be made and more importantly how. It directly instils knowledge of constructional constraints and architectural possibilities that can inform feasible designs. Examples are casting procedures and applying reinforcement. Although these constraints and underlying rules (i.e. the design space) can be embedded in digital tools, the danger exists of users becoming distanced from practical reality and treating tools as black boxes void of context. This can lead to impractical designs or can stifle imagination. Physical models therefore offer an important method of informing architects and engineers how to design and construct efficient and feasible fabric formworks. However, physical models are subject to physical constraints such as space, time and budget. This means that within an actual project, carrying out physical models might be unrealistic. Digital models offer the promise of simulating limitless concepts, under correct physical conditions, allowing large-scale designs to be envisioned.

An ideal situation would probably be the complementary use of both digital and physical models, where disadvantages of either are cancelled out. This requires better understanding of the inaccuracies and assumptions inherent in scaled physical models and in virtual digital models, and how these interact. An interesting factor in this discussion is the increasing availability of affordable 3D scanners allowing one to digitize the material for verification and/or analysis.

### 7.2 Accurate versus interactive modelling

The problem encountered in many of the existing examples is that of accurately predicting the physical models in the computational design setup. Examples with quantitative results are lacking, but from the examples in Section 3.4 it is clear that despite reliance on advanced, commercial software, it remains difficult to predict the physical outcome based on a digital model. Possible causes for disagreement are inaccurate modelling of material behaviour and tolerances of the boundary conditions, loading, cutting patterns and connections, but their relative influence on overall precision is unclear. This is a result of the fact that available software and plug-ins have not been developed for the particularities fabric formwork and may therefore present inappropriate form-finding approaches and results.

To develop a practical set of design tools, the degree of precision should be dictated by the computational power available so that the design tool can remain real-time and interactive. This is crucial if computational design is to be flexible such that it does not stifle creativity of users. Whether the resulting accuracy is acceptable can be discussed once numerical errors and deviations from physical results are quantified, and then compared to conventional tolerances in the construction industry.

### 7.3 Continuity of future software development

The proposed framework and early work shown here are intended to verify academic work. This has the benefit of providing reproducible numerical methods for design of fabric formworks. Although this means that it is free to be developed and improved upon further by anyone, one cannot assume directly that beyond this research project it will be maintained and modified for future purposes. The small number of potential users at this time creates little to no commercial incentive to launch a software product with continuous development and support. However, should fabric formwork become a more common building method, commercial software might follow, either new or integrated in other related products. Also, an increasing amount of open-source form finding applications has been developed in online communities such as Grasshopper and Processing. With no financial incentive at all, many people share their work nonetheless and build upon that of others.

And since the numerical problems associated with the design of fabric formwork are closely associated with those of popular form-active structures, it is reasonable to assume that new tools will become available or that existing tools will be adapted. Their usefulness, in our opinion, depends entirely on active participation of those working on fabric formwork in these communities.

## 8 Conclusions

The development of tools for the design and analysis of fabric formworks may be one prerequisite to allow for more common use of fabric-formed structures. However, existing uses of digital modelling of fabric formworks are rare. From these examples it is clear that accurate numerical modelling is challenging. Also, to perform the three tasks of form finding, analysis and patterning, one is often forced to construct a digital workflow consisting of sequential steps in different programs and/or custom written scripts, making computational design less interactive and straightforward.

To allow for (ideally real-time) interactivity, future design tools should integrate all design tasks in one platform and offer intuitive, visual feedback of the impact of design choices. Three design scenarios have been identified, each of which a design tool should be able to solve. Furthermore, three key aspects of fabric formworks in which they differ from analogous problems such as tensioned membrane structures have been discussed. As first steps towards a future design tool, a 2D parametric tool and a 3D framework have been set up. The 2D parametric model allows the design sections of prismatic fabric-formed columns or beams, and results will be used to inform how future interactive, parametric interfaces should be developed. The 3D design model allows the form finding of arbitrary cases of the first design scenario, where the initial geometry and fabric stiffness are known. It solved in principle each of the three key differences discussed, but also indicated challenges in accurate representation of wrinkles and in flexible approaches to patterning of the fabric. Refinement of these numerical approaches should be directed in such a way that the final design framework arrives at a balance between numerical precision on the one hand and interactivity on the other.

The authors believe that such a framework will complement and augment physical modelling in future design processes and will ultimately aid in unlocking the full potential of fabric-formed architecture.

## 9 Acknowledgements

The authors would like to thank Professor Mark West and Ronnie Araya for involving us in the Women Newborn Hospital project and for subsequent correspondence on the role of physical and digital models in fabric formwork design. Anne-Mette Manelius from the Royal Danish Academy of Fine Arts in Kopenhagen, Denmark, provided further discussion on the use of physical versus digital models. Some of their experiences and insights provided content for the discussion in Section 7. Finally, Claudia Ernst, Kyle Sturgeon and Shajay Bhooshan are acknowledged for detailing their digital workflow of the Digital Plaster, FattyShell and Hyperthreads projects respectively.

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