# Fabric formwork for flexible, architectural concrete

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ABSTRACT: An innovative research project scanned the possibilities to use fabric as a flexible formwork for architectural concrete elements. Besides a general feasibility study, the project focuses on the textile parameters such as stiffness and permeability, the quality of the concrete surface and the modeling of the formwork both before and after casting. For this, the project gathers together textile industry, architects and contractors, to combine architectural creativity and modern technology. The first laboratory tests show the potential of the concept, and a range of different shapes of formwork and concrete elements. A series of case studies has been elaborated to deal with issues as textile choice, shape modeling, textile pretension, formwork fixation, concrete application and more. This article presents a general outline of fabric formworks and the details for some case studies such as architectural columns and double curved shells.

## 1 INTRODUCTION

There is an increasing demand for creative and organic shapes in modern architecture, although it is not always easy to realize the architect designs. Theoretically, concrete is the perfect material to make all kind of various shapes since, after all, fresh concrete can be poured into any formwork shape. Traditional formworks however are very stiff and straight-lined, rendering flat walls, and rectangular beams or columns. These panel formworks are often the limiting factor for more organic architecture.

Moreover, it could be stated that creative architects often deliver quite eye-catching designs that cannot be realized due to formwork limitations. A Belgian example is the design of the Ghent Music Centre by Toyo Ito (Figure 1), which has been rejected.

Figure 1: Not retained design for the Ghent Music Centre (Copyright Toyo Ito in cooperation with prof. Andrea Branzi).

Flexible fabric formwork might create new possibilities for designers and contractors to realize these kind of organic shapes. A limited number of researchers explored worldwide the possibilities of fabric formwork. In Canada, Professor West used fabric formwork to create architectonic panels, columns and beams (see Figure 2). Some case studies have been done in Edinburgh (Pedreschi 2005) and Delft (Pronk, 2005). Furthermore form-finding software tools have been used for the analytical modeling of fabric formwork (Schmitz, 2004).

Figure 2: Plaster models of lightweight trusses made with fabric formwork (West 2006).

Fabric has already been used since decades for forming cast-in-place structures, as for instance for slope or dike reinforcement, preventing the wash-out of the concrete under water. Using the flexible formwork for the actual shaping of architectural concrete elements is a rather recent and innovative trend.

The use of fabric formwork has several advantages:

- Shape flexibility: changing column diameters, curving surfaces for panels or complex shell structures are nearly impossible to create with traditional formwork.

- The surface quality of the concrete: fabrics can modify the texture of the concrete, minimize the number of air bubbles or increase locally the water/cement-ratio like a CPF (Cairns, 1999). The effects largely depend off course on the type of fabric used.
- Transport: the weight and volume of the fabric formwork is very small compared to wood or steel, creating export opportunities. Additional falsework is however still needed.

## 2 MODELING AND SHAPING

An important modeling stage precedes the actual formwork building. The modeling defines the formwork shape for fabric assembly, and calculates both formwork deformations during the application of the concrete, and the necessary pretension of the fabric. This fabric (pre-) tension is an important issue to consider for each design: first of all, the fabric can only be loaded with tensile stresses. The deformation of the fabric after the application of the concrete can furthermore only be limited with sufficient pretension of the fabric.

In the framework of this project, the same approach as used for modeling textile architecture has been used, based on textile parameters (mainly bi-axial stiffness) and loading conditions (concrete cover in stead of wind or snow load). The modeling process, calculating an equilibrium state for a membrane, is based on the "force densities" method, which starts the calculation from a pin-pointed or cable network (Gründig et al., 2006). Taking into account a number of boundary conditions, maximum stresses and deformations for the membrane and resulting forces on the borders are given by these calculations (Figure 3).

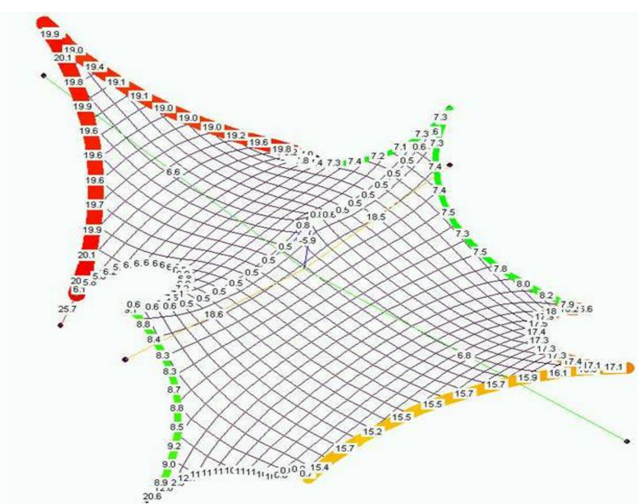

Figure 3: Software modeling of textile architecture

The software model is finally used for the cutting patterns that allow for the actual fabric formwork building. Some real simple shapes like straight-lined columns can be made out of one single piece of fabric. Most other elements however need a specific shaping of the fabric, for which the complete structure is subdivided in fabric pieces and recomposed afterwards. Several methods exist for creating these cutting patterns (Gründlig, 1996). Figure 4 shows the simplified example of creating the pattern (1/12$^{th}$) for an axial-symmetric column.

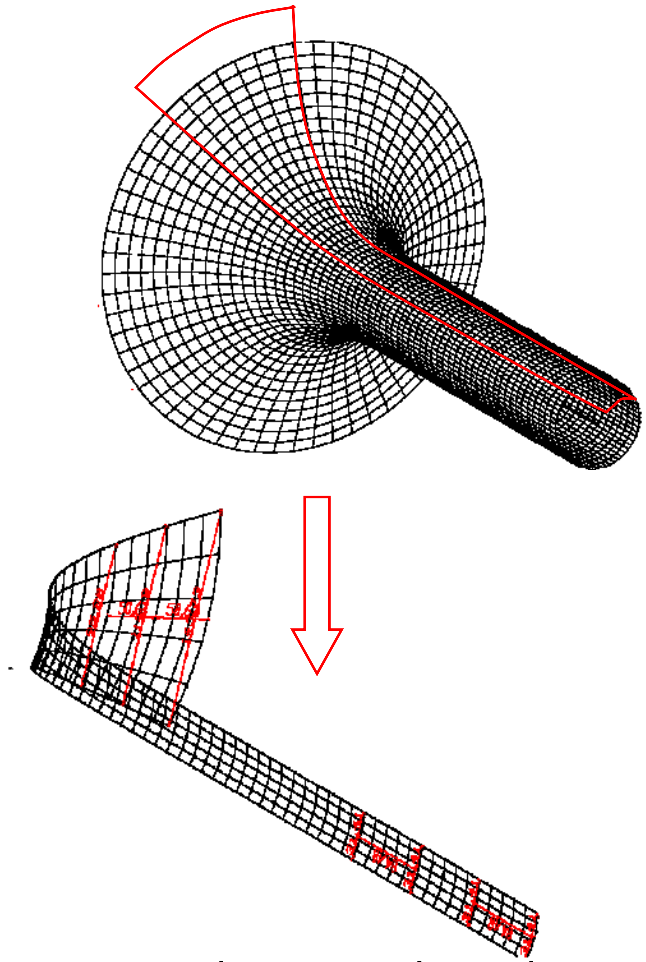

Figure 4: Creating the cutting pattern for an axial-symmetric column.

## 3 MATERIALS

### 3.1 *Fabric requirements*

Depending on the type of concrete elements to be cast, some minimum technical requirements for the fabric formwork can be listed:

- High Young modulus, reducing the deformations after concreting. This is very important for shell structures, but less important for columns.
- A well-adapted surface quality, allowing for a good demoulding of the concrete. Furthermore reusability and surface enhancement depends on the permeability of the fabric.

Because of these requirements, fabric types with rather high tensile strength (40-150 kN/m) at low deformations (18-30%) are selected. The Young modulus ranges between 0.1 and 1 GPa and the stiffness between 135 and 550 kN/m. These results are based on unidirectional tests, bi-directional tests will be performed later.
Both coated and non-coated woven PP, PE and PVC are used. The coated fabrics are impermeable and can give smooth or textured concrete surfaces. The non-coated fabrics are slightly permeable.

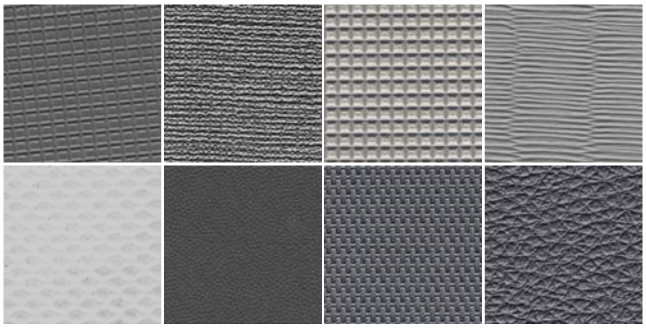

Figure 5: Different patterns for coated, woven textiles.

### 3.2 *Fabric assembly and formwork building*

The formwork preparation usually includes a assembly step for sewing or welding the fabric pieces, starting from the cutting patterns (see §2). Depending on the fabric and coating type, stitching or welding is chosen for the assembly. Figure 4 shows the head of a stitched column, assembled out of four parts. This assembly step could even allow for the integration of local reinforcements like ropes or cables, the production of double layers, or the inclusion of accessories like fixations. A secondary construction, the falsework, allows furthermore for the fixation of the fabric and the application of any pretension.

Figure 6: Stitched column head

This approach might facilitate the on-site placing and concreting, and limits the need for secondary constructions. An integration in a panelized formwork for flooring systems could be aimed at. An alternative approach is the use of wooden supporting structures to shape the columns (West, 2006).

## 4 EXPERIMENTS

In a first stage, some elementary testing showed a good to perfect surface quality for all textile types: nearly no blow holes or surface defects and a perfect imprint of the textured textiles. Different textile types have been used for sample preparation, in order to perform further durability tests. In a second stage, several case studies focused on the practical implementation.

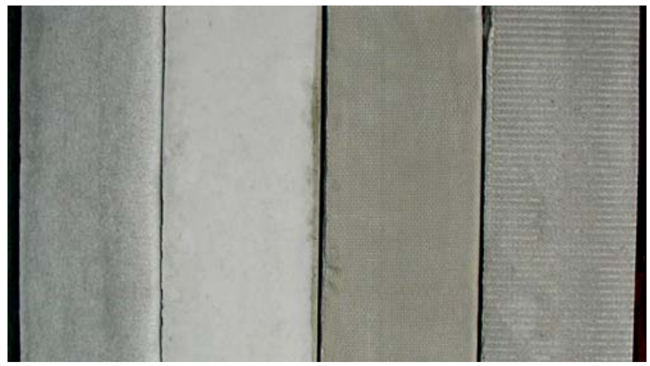

Figure 7: Concrete samples with different textured surfaces.

### 4.1 *Case study 1: columns*

The realization of a series of columns with prefabricated fabric forms illustrates some of the key point advantages of fabric formwork:

- Shape flexibility: several diameter adaptations have been used, and even rectangular upper or lower heads.
- Surface quality, especially when using self-compaction concrete. Demoulding never gave any problems.
- Reusability of the fabric, when using systems like zippers or other to facilitate the demoulding.

Shaping and cutting pattern creation of the columns has been done with software (see also Figure 4). Both circular and rectangular columns have been created, and most fabric formworks have been composed out of 4 pieces via welding and stitching. Figure 8 and Figure 9 show the completed fabric formworks after assembly and a zoom of the result after demoulding. The small imperfections of the concrete surface are due to a lack in pretension of the fabric formwork.

Figure 8: Prefabricated fabric moulds for columns.

Figure 9: Demoulding of the fabric formed concrete column.

## 4.2 *Case study 2: double-curved shells*

The realization of complex shell structures, directly derived from textile architecture, is even more challenging. The starting point remains the modeling of the shell, resulting in a pattern for the assembly of the fabric shape and in the minimum required formwork pretension in order to minimize the deformations when applying the concrete.

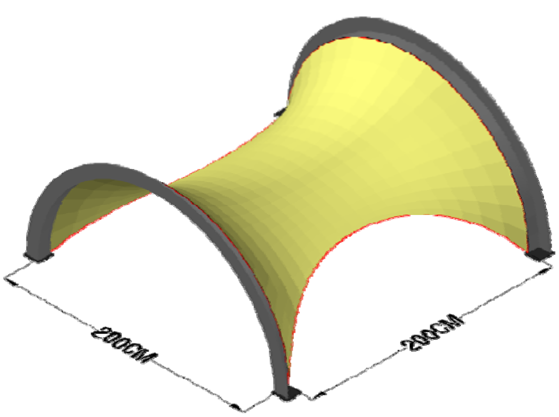


Figure 10: Design for a double-curved shell.

Figure 10 shows the design model for one of the case studies. Figure 11 illustrates the calculation model, with indication of the stresses in the membrane and the resulting forces on the borders.

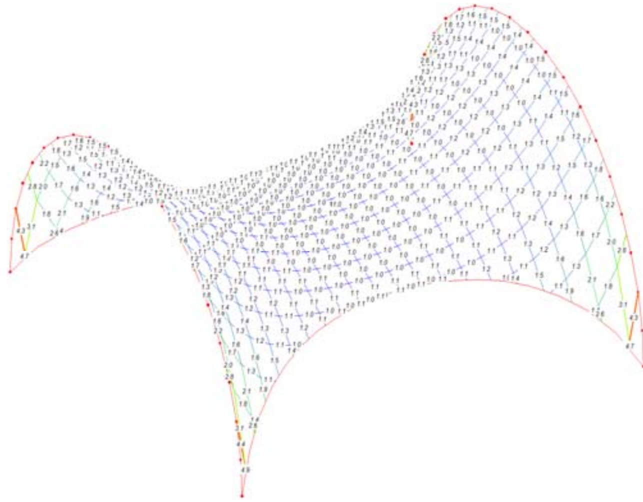

Figure 11: Calculation of the stresses in the membrane and the resulting forces on the borders.

A coated textile with a Young modulus of 0.1 GPa and a stiffness of 150 kN/m has been used for the laboratory tests. The fabric for the formwork has been composed out of 3 pieces, a minimum to guarantee the shape (see Figure 12). The more fabric pieces are used, the better (highly) curved shapes can be approached. An integrated rope and keder ensures for a good fixation at the (two) borders.

Figure 12: Fabric formwork for the double-curved shell.

Fabric pretension has been applied with a set of load cells. These cells also monitor the additional load during the casting process. Figure 13 shows the final formwork configuration, ready for concreting. Shotcrete has been used for the concreting, applied in several layers, up to an overall thickness of 5 cm. The maximum deflection after concreting was only about 2 cm in the middle of the arch, which means our software model tends to overestimate this value.

Figure 13: Fabric formwork, pretensioned using a secondary structure.

Other types of textiles will be used for further testing, evaluating the conformity of the modeled values for deformations and force distributions.

Different types of reinforcement will be included as well in further work, comparing the feasibility of integrating for instance traditional steel rebars and innovative textile reinforcement.

The illustrated techniques could be used for on-site construction of curved elements, columns and shells. The concept could be applied as well for precast production, for instance for producing half-fabricate products.

## 5 CONCLUSIONS AND OUTLOOK

Fabric formwork can create new possibilities for the shaping of concrete elements and architecture. The first experiments are promising, and confirm the possibility to create a variety of shapes. Software models can be used to shape the elements, and to calculate both maximum stresses in the fabric and minimum pretension for the conservation of the shape. Cutting patterns are furthermore the basis for the assembly of the actual fabric formwork, by stitching or welding.

The construction of simple concrete elements, as for instance columns, is possible without any difficulty. This study also illustrated the feasibility of producing more complex structures like double-curved shells, that are nearly impossible to make with traditional formwork. These structures need however a thorough preliminary study, focusing on stresses in the fabric and shape control during concreting.

## 6 ACKNOWLEDGES

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