Shell elements of architectural concrete using fabric formwork–part 1: concept

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FABRIC FORMWORK FOR FLEXIBLE, ARCHITECTURAL CONCRETE

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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's designs. Theoretically, concrete is the perfect material to make all kind of various shapes, since after all, fresh concrete can be poured into any type of formwork. Traditional formworks however are very stiff and straight, rendering flat walls, beams or other elements, and are often the limiting factor for more creative ideas.

One of the most interesting applications of this technique is the production of thin, double curved shell elements, which are difficult to produce with conventional formwork techniques. These shell elements can be used as façade panels, as self-bearing roofing structures, or as permanent formwork elements. In the latter case, large spans can be realized, with very appealing designs and a perfect surface finish.

Some researchers worldwide explored the possibilities of fabric formwork. In Canada, pioneering professor West used fabric formwork to create architectonic panels, columns and beams (Fig. 1). Some case studies have been done in Edinburgh [2] and Delft [3]. Furthermore form-finding software tools have been used for the analytical modeling of fabric formwork [4]. An innovative research project investigated the possibilities to use textile as a flexible formwork, focusing 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, and the difficulties integrating (traditional) reinforcement.

Fig. 1: Plaster models of lightweight trusses made with fabric formwork (West 2006).

3 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 pretension 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 self weight instead 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 several boundary conditions, maximum stresses and deformations for the membrane and resulting forces on the borders are calculated.

The software model is finally used for making the cutting patterns that allow for the actual fabric formwork production. Some 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). Fig. 2 shows the simplified example of creating the pattern (1/12th) for an axial-symmetric column.

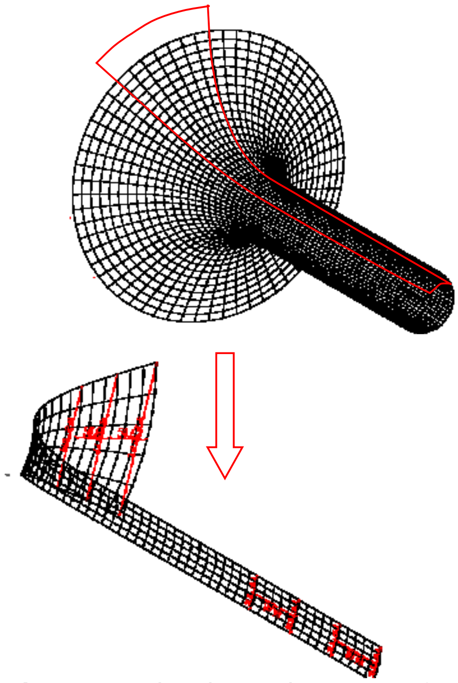

Fig. 2: Creating the cutting pattern for an axial-symmetric column.

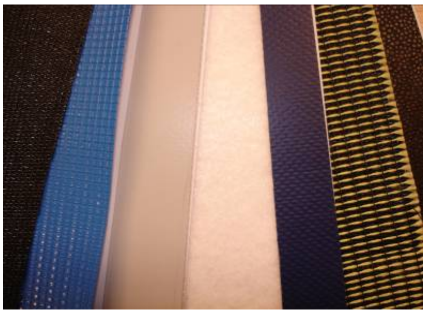

Fig. 3: A wide range of different fabric types can be used.

Fig. 4: Stitched column head

4 MATERIALS

4.1 Fabric requirements

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

- High elastic modulus, reducing 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 elastic modulus ranges between 0.1 and 1 GPa and the stiffness between 135 and 550 kN/m, based on bi-directional tests. 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.
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 for instance a CPF (“controlled permeable formwork”). The effects largely depend 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.
- Design optimization: the shape flexibility allows for designers to correlate member design and structural aspects. A beam formwork could take into account the actual moment curvature, and column heads could be designed to reduce problems with punching.

4.2 Fabric assembly and formwork production

The formwork preparation usually includes an assembly step for sewing or welding the fabric pieces, starting from the cutting patterns. Depending on the fabric and coating type, stitching or welding is chosen for the assembly. Fig. 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.

5 REALISATION OF DOUBLE-CURVED SHELLS

The realization of complex shell structures, directly derived from textile architecture, is one of the most challenging applications for this technique. The starting point remains the modeling of the shell, resulting in a pattern for the assembly of the fabric shape and in the required formwork pretension in order to minimize the deformations when applying the concrete. Fig. 5 shows the design model for one of the case studies. Fig. 6 illustrates the calculation model, with indication of the stresses in the membrane and the resulting forces on the borders.

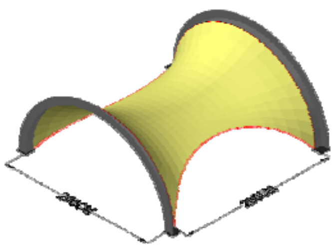

Fig. 5: Design for a double-curved shell.

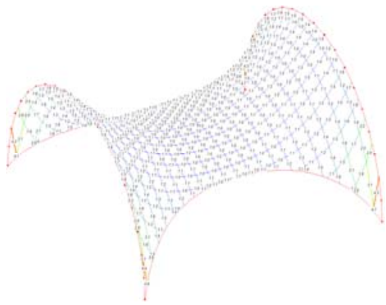

Fig. 6: Calculation of the stresses and forces.

Fig. 7: Fabric formwork for the double-curved shell.

A PES textile, PVC coated, with an elastic modulus of 0.1 GPa and a stiffness of 150 kN/m has been used for the laboratory tests. A pretension of about 1.5 kN/m has been used. The fabric for the formwork has been composed out of 3 pieces, a minimum to guarantee the shape (see Fig. 7). The more fabric pieces are used, the better (highly) curved shapes can be approached. An integrated rope and glass fiber bar ensures for a good fixation at the two borders.

Fig. 8: Pretensioning the fabric with a secondary structure.

Fig. 9: Shotcrete application

Fig. 10: Shell after demoulding.

The fabric pretension has been monitored with a set of load cells at one end of the secondary structure. These cells also monitor the additional load during the casting process. Fig. 8 shows the final formwork configuration, ready for concreting. Shotcrete mortar has been used for the concreting, applied in several layers, up to an overall thickness of 5 cm (maximum aggregate diameter of 2 mm, average compressive strength of about 30 N/mm²). Displacement sensors monitor the vertical deformations during the concreting. The maximum deflection after concreting was only about 2 cm in the middle of the arch, which corresponds well with the software modeling.

For the whole project, four different fabrics have been used for the confection of ten shell elements, with reasonable correlations between calculation and measurement of the deflections for most fabric types. The measurements showed deviations between 5 and 58 %, on a calculated deformation of about 15 mm for a span of 2 meter. Part of this deviations is attributed to slip at the fixation points, and the dynamic effects of the shotcreting. The deflection for the non-coated fabric however showed a large deviation (more than 100 %), probably due to a larger slip at the fixation points. Further improvements for a better control of the deviations could be important for large spans.

The experiments included the integration of two types of reinforcement, comparing the feasibility of integrating traditional steel rebars and innovative textile reinforcement. The second part of this article will give more details on those case studies [7].

6 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 such as columns and shell elements. Software models can be used to shape the elements, and to calculate both the stress distribution in the fabric and the minimum pretension to apply. This pretensioning of the fabric formwork reduces the deformations when concreting. Cutting patterns are furthermore the basis for the assembly of the actual fabric formwork, by stitching or welding.

Only a limited preliminary study is needed for the production of uncomplicated concrete elements, as for instance straight-lined columns. This study focused on 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.

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 special types of permanent formwork products. In that way, the advantages of both precast quality and on-site processing can be combined. For precast plants, fabric formworks allows for fast changes in element shapes. In a next research step, the integration of the reinforcement should be studied more in detail, evaluating among others the use of the formwork as part of the actual reinforcement, as a kind of polymer reinforcement. The structural performance of thin shell elements could probably be optimized using high quality concrete types such as UHPC, while the integration of polymer reinforcement reduces the necessary concrete cover.

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