Fabric Formwork for Concrete

Fabric formed concrete structures and architectural elements

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ABSTRACT: Fabric formwork is a rapidly evolving technology that challenges the conventional approach to the production of concrete structures and elements. This paper presents the outcome of a prolonged series of studies. The technology and its expression is examined through a series of creative studios with senior architecture students and more detailed complimentary studies on structural behaviour. These studies include investigations into surface texture and finish, the design, development and construction of large-scale prototypes, beams, columns, walls and shells as well as the structural development and testing of form-active beams. Fabric formwork is an effective and expressive technology, one that can be applied in a wide variety of applications. It demonstrates the characteristics of a disruptive technology, one that challenges the existing paradigm, in this case the predominance of rigid formwork.

1 INTRODUCTION

Of all the common construction materials concrete is the most widely used, according to the European Cement Association global production of cement in 2011 was 3.6 billion tonnes. Cement manufacture is an energy intensive process, it is the main contributor to the carbon footprint of concrete. The remaining ingredients, sand, aggregates and water are generally sourced locally, require little processing and contribute less to the carbon footprint. One reason for the global reach of concrete is the relative ease by which it can be produced. Adding water to the dry ingredients creates ‘liquid stone’ a material of almost limitless shape that subsequently sets due to the hydration of cement to form this strong and durable material. At one end of the spectrum of possible construction technologies, concrete can be a very low technology-low capital material. At the other end it can be highly crafted and engineered used in some of the most technically sophisticated of projects. Arguably the most significant factor on the range of possibilities of concrete is the fifth element, the formwork, used to support the wet concrete, define its shape and determine the quality of finish. In practice the range of forms and geometries possible is controlled by decisions regarding the formwork. Conventional formwork is most often constructed using planar rectangular components in timber or plywood leading to flat rectangular forms. Complex curved geometries may provide more efficient structural forms and more interesting architectural components but are generally more expensive due to the additional efforts needed to manufacture the formwork. An alternative approach is to use flexible formwork using textiles. At first glance textiles may seem to lack the robustness needed to support a heavy and abrasive material such as concrete but it is surprisingly effective. The flexibility of the fabric responds to the hydrostatic pressure of the concrete and deforms to the most efficient shape to carry the load, Furthermore the permeable nature of the fabric acts as a filter that allows the excess water in the concrete mix to escape during casting, reducing the hydrostatic pressure on the formwork. Furthermore the permeability of the fabric encourages the passage of trapped air, which together with the reduction in the water/cement ratio produces a more durable surface finish with fewer defects. In recent years there has been a growth in both the applications and research in the use of flexible formworks. This paper describes a prolonged investigation into the development and use of textiles as formwork at the School of Architecture, University of Edinburgh.

2 BACKGROUND TO FABRIC FORMED CONCRETE

2.1 *The development of fabric formwork*

Detailed reviews of the history of fabric formed concrete are given by Veenendaal (2011) and Abdelgader (2008). One of the earliest applications of fabric formed concrete in building was by the Irish engineer James Waller, Conlon (2012). He developed a number of interesting applications using fabric as formwork, perhaps most notably the Ctesiphon roof system, first used in 1941. The system comprises a series of catenary ribs with hessian fabric draped between. Concrete is applied directly to the hessian, which sags between the ribs to form a corrugated arch construction typically between 70-90 mm in thickness and spanning over 20 metres. Quite a number of these were built during the 40s and 50s and a variation was developed by Felix Candela in Mexico. The Spanish Architect Miquel Fisac, in an effort to break from the rigid discipline of wooden forms explored through, both design and construction, the possibilities offered by the flexible formwork, Garćia Carbonero (2003). Many of his projects, between 1970-90, used flexible formworks to produce highly articulated cladding panels by restraining the deformation of the formwork during casting. Flexible formwork is used in a variety marine applications where access using conventional rigid formworks would be more difficult, such as breakwaters, and pile jackets in building systems to produce circular columns, Abdelgader (2008). In recent years there has been considerable growth in the interest in the use of flexible formwork, led by the pioneering work of Mark West from the University of Manitoba and the formation of CAST, the Centre for Architecture and Structural Technology. A clearly defined network of researchers is developing with international conferences, the formation of the International Society of Fabric Forming, and a number of recent doctoral completions, Lee (2011), Hashemian (2012), Manelius,(2012) and Orr, (2012).

2.2 *Characteristics of fabric formwork*

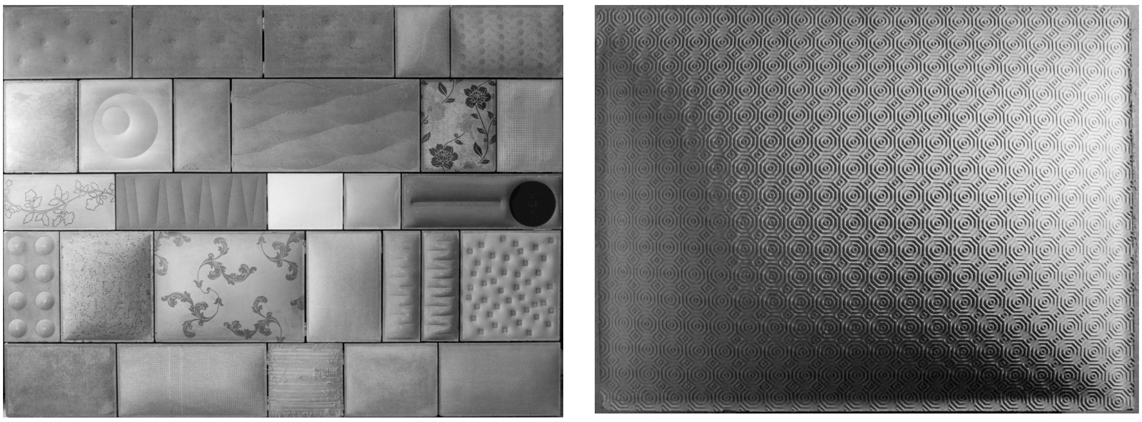

Figure 1 Fabric formwork wall showing texture and variety of finish plus close up of panel

The use of flexible permeable formworks has considerable benefits in comparison with conventional rigid systems.

- Formwork is lighter and easier to construct. The fabric can carry only axial tensile forces and as concrete is placed the fabric deforms to the optimum geometry in response to the hydrostatic pressure of the wet concrete.

- By careful shaping of the fabrics optimised structural forms can be developed that would otherwise be very expensive with conventional systems.
- The permeable nature of the fabric allows the excess water needed to place the concrete to bleed, reducing the water cement ratio of the near the surface, thereby increasing the compressive strength of the concrete in the surface layers. A review of the benefits of permeable formwork systems has been prepared by Malone (1999).

It is possible to use many types of fabrics, from upholstery and dressmaking through to engineered textiles. The type of fabric will also influence the surface finish, patterns and textures on the fabric will transfer to the concrete. As part of the research at the University of Edinburgh a wall was created using a proprietary rain-screen cladding system to demonstrate the range finishes and textures, Figure 1. The most common type of fabric used is woven polypropylene, developed initially for geotextile applications. It is robust, does not tear readily, has a controlled permeability, consistent mechanical properties and is easily stripped from the hardened concrete surface.

3 STUDIES AT THE UNIVERSITY OF EDINBURGH

The underlying technology of fabric formwork presents many opportunities for research and practice, straddling both structural and architectural applications. The inherent simplicity of fabric forming and its unconventional nature suggests new methodologies for research and exploration. It is not a substitute for rigid formwork nor does it require the same exigencies. To some extent it represents a significant paradigm shift that its development will not be conditioned by adaptation of existing practice. Fabric formwork is an example of a 'disruptive technology'. This term was first used by Christensen (1997) to describe technologies that evolve away from the mainstream, often from non-traditional sources and ultimately challenge the original predominant technology. The studies are concerned with understanding the key factors that make for effective application of the fabric formwork in a variety of architectural and structural applications, thereby establish an appropriate technological framework. The recognition that fabric formwork is a Disruptive Technology encourages a novel research methodology to be used. A sustained series of projects has been undertaken with post-graduate students of architecture in which they design and develop architectural components by prototyping and testing leading to the production of a major piece as close to full-scale as possible. Projects are run on a full time basis over a six-week period, during which the students rapidly learn detailed knowledge of concrete, construction process and detail. Each group of students then prepares a detailed reflective report, which forms part of the input into subsequent projects. The students are guided through regular tutorials and reviews helping them to both develop a research methodology and develop their final design. The concrete technology is kept quite straightforward with a typical mix being in proportion to stone, sand and cement 10:5:4 with an initial water/cement ratio of just over 0.5, the mix tends to have a comparatively high of workability with excess water being lost during the casting process. More recently plasticiser has been used where the casts have been particularly complex in form. A further series of projects has been undertaken to study the structural behavior of elements such as beams and columns. Further information on early studies can be found in Chandler and Pedreschi (2008).

4 PROTOYPE STUDIES

4.1 *Classification of prototypes*

An aspect of the disruptive nature of the research is the terminology that describes both the processes of the construction and the forms of the elements created. The language used to describe the fabric formwork is evolving. By organising the research around a set of open studies exposes a wide range of issues that defining characteristics of the technology can be determined.
These include:

- Fabric shaping
- Material properties of the fabric
- Degree of control of the fabric

- Pretension in fabric
- Component precision
- Complexity of form
- Sequence of filling and control of fabric during casting

When developing a design these issues help frame the approach to the formwork and method of casting.

4.2 *Column elements*

A variety of columns element have been developed and constructed. In its simplest form a rectangle of fabric folded once and joined along one side if supported at the top will produce a cylindrical column and indeed such formwork is available as a product in Canada, marketed by Fab-form. The hydrostatic pressure developed during casting creates uniform circumferential stresses in the formwork.

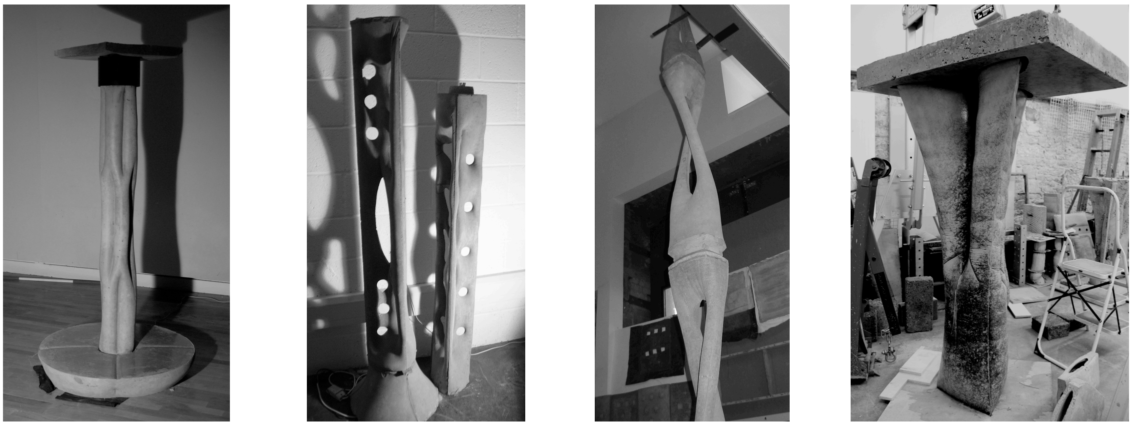

Figure 2 Various columns using fabric formwork, annotated (a) to (d) from left to right.

By controlling the deformation of the fabric the surface can be modeled in very interesting ways, Figure 2(a). The flowing ribs are created using laser cut plywood stiffeners carefully positioned around the formwork that controls the deformation of the fabric is a precise manner. Figure 2(b) illustrates the use of clamps to produce a highly stylised form of perforations. The formwork is assembled using three sheets of fabric with alternating edges of fabric connected using clamps made from plywood strips running the full height of the columns. These strips support the opening at the top of the column through which the concrete is poured. Perforations are formed by the use of clamps connecting two sheets fabric. Great complexity in the geometry can be produced with a set of very simply produced clamps. Figure 2(c) shows the use of pretensioning. The formwork is made from a single sheet of fabric, stitched to create a cylinder. Further stitching within the body of the formwork creates a large void. The formwork is stretched vertically between plywood plates at the top and bottom of the column in a purpose designed rig. Further tension in the formwork is produced by rotating the top plate relative to the bottom. The figure also illustrates component precision as the columns elements can be stacked one top of each other using a very precise interlocking male and female joint. The finished assembly consists of four sections that are completely modular in nature and interchangeable, yet each one is purposefully different. Figure 2(d) presents a column where the fabric has been tailored to create a flared head, rising from a central cylindrical section and dividing into three separate branches. The term column can be used to describe both the structural element and the process of construction. The latter implying an essentially vertical component filled from the top in its final orientation. Clearly some of the column elements in Figures 2 would have quite markedly different load carrying capacities. As series of studies has recently been undertaken to study the structural behavior of short, non-prismatic circular columns.

4.3 *Beam elements*

Similar to the columns the term 'beam' can be used to describe both the structural element and the process of forming. Casting relatively shallow, horizontally orientated elements is comparatively simpler vertically alighned column elements. The apertures through which the concrete is placed are larger and the distance the concrete travels within the concrete is shorter that in elements cast as columns. Depending on the design, vertically oriented panels maybe more easily cast as beam elements such as the panels for the RHS Chelsea, Figure 3.

Figure 3 Wall panels constructed for Royal Horticultural Society Chelsea 2009

Beams as structural elements have been studied by a number of researchers, Orr (2012), Hashemian(2012) and Lee(2011). Lee, based at Edinburgh used flexible formwork to develop a very efficient form-active geometry through successive incremental modification of the form.

Figure 4 Form-active beams:, left(a) Initial geometry, right (b) Initial and final geometry

The initial cross section was T-shaped with a rectangular flange, Figure 4(a). The depth of the web followed a parabolic profile reducing in depth from a maximum at mid-span to the thickness of the flange at the supports, following the shape of the bending moments for a distributed load. Having a flat flange at the end of the beam was considered essential for practical reasons to allow adequate bearing and connection to any supporting structure. The beam was reinforced using curved primary steel that followed the profile of the web. Structural testing indicated anchorage failure in the flange at the reactions points. In subsequent tests the structural performance was improved by progressive modification of the geometry and detail. These include:

- Improvements in the detail of the anchorage of the bars.
- Changing the angle of reinforcement at the anchorage point reduces the force in the flange.
- Increasing the thickness of the flange locally at the reaction point, Figure 5(b)

There was a progressive increase in load carrying capacity. The failure mode changed from anchorage to one of shear – flexure. The final modification was a change in geometry of the web. As the web moves towards the support points it reduces in depth but increases in width. Again at the reactions the beam reduces to simply the thickness of the flange. The final change resulted in a ductile failure mode with steel yielding at the mid-span of the beam. In other studies, using form-active geometry emphasis has been placed on optimising the geometry primarily from the perspective of the bending force actions and these too have experienced shear failure at the reactions. In the studies at the University of Edinburgh the geometry of the beam was modified progressively to improve shear performance. The final profile of the beam reflects both the bending force actions and the shear force actions. The resultant geometry is quite complex. The width and depth of the web vary continuously and the underside of the flange curves upwards from the reaction. Thus the junction between the flange and the web follows a quite complex path. The final design of the beam therefore achieves its full flexural capacity without any shear reinforcement and optimal use of concrete. A comparison was made with an equivalent rectangular T beam of equal structural strength and it was found that the embodied energy of the fabric formed beam reduced by approximately 35%.

What is particularly of note is the comparative ease by which the progressive improvements to the geometry were made. In structural optimisation the use of materials can be minimised by developing forms that generate uniform stress distributions and eliminate excess or unnecessary material. However these forms often come as the cost of more expensive construction. It is self-evident that the beams developed at Edinburgh would have been would have been very expensive to construct using conventional rigid formwork and the particular research methodology of progressive modification of the formwork would not have been possible given normal budget constraints. The work therefore demonstrates the inherently disruptive nature of the technology very effectively. The intrinsic simplicity of the final beam geometry relied on an understanding of the shaping and development of the fabric rather than the skill and expertise needed to shape flat panels into curved forms.

4.4 *Shells*

In the development of modern concrete construction shell structures, perhaps more that any other typology, demonstrated the expression of the plastic nature of concrete. The curved surfaces and predominantly axial compressive forces suggest similar characteristics to traditional vaulting they differ in one particularly important way; their thinness in relation to span. Angerer (1961) suggested a new classification and called them surface structures, where the inner and outer surface would be almost the same, only differentiated by the minimal thickness in between. When based on geometrically correct structural principles these shells were optimised demonstrated wonderfully in the work of Candela and Isler for example. However again the shape can be resolved but often production of the formwork poses the most difficulty in their realisation. Fabrics can be used to create complex curved shapes that correspond to the form active geometries of shells. Figure 5(a) shows a prototype shell the geometry of which is based on the Gaussian vault, developed by Eladio Dieste, Pedreschi and Theodossopoulos (2010).

Figure 5 Shell using fabric formwork from the left (a) Gaussian, (b) Hypar, (c) Dome

The structure is defined by two catenary curves of equal span but differing rises. Two profiles made from plywood are cut to follow the catenary lines are then used to define the two leading edges of the shell. The edge profiles then form part of a braced formwork system. The fabric is stretched across the edge and pre-tensioned against the sides of the frame. A second plywood profile is attached to the first, providing additional clamping of the fabric. The second profile of the fabric is carefully offset from the first profile to provide a very accurate control over the edge thickness (35 mm) of the shell. The concrete was applied in a series of layers directly onto the fabric. A series of preliminary tests had been carried out to determine a suitable mix and textile combination for best adhesion on the sloping surface of the formwork. A mix of 2.5/4.5 cement/coarse sand was found to be suitable. The process can be applied to other forms of shells. Figure 5 (b) shows a hyperbolic paraboloid shell, typified in the work of Felix Candela.

The formwork comprises four stiff timber edge beams. Two layers of woven fabric were stretched and tensioned between the timber beams, forming a hypar surface. A similar mix to the previous shell was applied directly onto the fabric in thin layers. The edge thickness was carefully controlled using pre-formed guide. The third shell is a segmented dome, Figure 5(c). In this example the fabric is again stretched and tensioned against edge timbers, which in this case also have to deal with the connections between adjacent segments and required careful detailing to ensure good fit.

Further research in underway looking at the development of technical textiles specifically for use as formwork, Soden et al, (in press) and re-deployable formworks combining textiles with gridshells, Tang (2012).

4.5 *Complex forms*

The previous examples have focused primarily on structural elements. Other studies have looked at complexity of form and complexity of construction. Figure 6 shows examples of each. Figure 6(a), a complex branching form. The formwork was produced from a single sheet of textile, folded over. The pattern of branches was drawn directly into the fabric used as a guide for stitching. The shape of voids and their position was determined partly by the need to ensure that the formwork would be filled without the fabric creasing or voids forming and was based on the results of a series of preliminary prototype studies into flow of the concrete in the formwork. Figure 6(b) illustrates a project where there is considerable complexity in construction and assembly. It is a prototype for a spiral staircase with inners and outer curved walls. The treads of the staircase are wedge shaped and span between and connect into the two walls. The difficulty is the need to ensure accuracy in the connection points for the treads, in a panel whose sides are made with flexible material. It requires the careful use of templates and setting out of the fabric to ensure that the template that locate the tread and the holes for the connecting bottle are fixed in the correct position and orientation prior to casting. All the components are cast separately prior to final assembly. The stair panels used three different textiles to provide differing functions. On the underside a more flexible fabric was used and the subsequent deformation provided additional stiffness. A stiffer fabric was used on the upper side to provide a flatter surface and the on the front end of the tread a highly textured fabric was used to provide additional resistance to slip.

Figure 6 Complex forms and construction, from left (a) highly complex geometry, (b) spiral staircase

5 SUMMARY AND CONCLUSIONS

This paper has described the key elements of fabric formwork for concrete and presented a variety of different types of elements that can be constructed using the techniques. The process was described as 'disruptive technology' and the work demonstrates that it challenges the conventional paradigm of rigid formwork. Most of the projects described in the paper were the product of a six week long workshop where that students had only a rudimentary prior knowledge of concrete and construction, yet by the end of the project managed to produce a wide range of complex and generally well resolved large scale prototypes. These include columns, beams, shells and walls. There is significant potential for fabric formwork simply to create an architectural finish to concrete, with an almost limitless range of textures and surfaces possible. Form active structures such as beams can optimise form whilst reducing construction effort. Pretensioning the fabric between stiff edges can be used to create a variety of shell forms. The technique needs also to be practical and conform to expected construction requirements for accuracy and precision, not immediately self evident when using flexible formwork. Its perhaps counterintuitive but the flexibility of the formwork actually leads the designer to consider precision at a much deeper level and identify where its resolution is most critical.

Further studies are underway to examine the development of particular textiles for formwork to facilitate construction and the behavior of non-prismatic circular columns.

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