

THE USE OF FABRICS AS FORMWORK FOR CONCRETE STRUCTURES AND ELEMENTS

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Summary. This paper presents and describes a series of studies into the use of flexible fabrics as formwork for concrete structures as alternative to conventional rigid formwork.

1 INTRODUCTION

Concrete is, arguably, the most significant of all construction materials, certainly it is the most ubiquitous of materials and is available in one form or another throughout both the developed and developing world. It has many excellent qualities. It is strong, durable and fire resistant and has good thermal and acoustic properties. Apart from cement its constituents are easily sourced and generally require little processing. In the history of architecture, contemporary concrete is a relatively new material, in effect dating back to the end of the 19th century. During its lifetime, from casting to component it exists in two states, an initial fluid condition and a hardened rigid permanence. During the initial state the concrete has to be held in a formwork that defines the final form. The formwork is responsible for the geometry, the surface, the texture and the overall finished quality of the piece. Despite its extensive use concrete has also received considerable criticism as architects ‘let concrete be concrete’¹, allowing the contemporary and often rough finish produced with conventional timber formwork to be expressed. This form of expression became known as ‘Brutalism’ and unfortunately also became associated with poorly constructed and poorly detailed projects. The poor reputation could also be attributed to the poor quality and execution of the formwork rather than the material itself. The established paradigm for concrete is to use planar timber forms. Perhaps there has been a mindset in builders that concludes that as the formwork is disposable and temporary it requires less care in execution. There are, however, many examples of very high quality concrete in architecture² and generally these examples require particular diligence in both design and execution. Thus a dichotomy exists in our understanding of concrete, between its ubiquitous use and the quality of its construction that is centred around the use of planar timber forms. The engineer Pier Luigi Nervi, described this situation,

‘It may be noted that although reinforced concrete has been used for over a hundred years and with increasing interest during the last few decades, few of its properties and potentialities have been fully exploited thus far. Apart from the unconquerable inertia of our

*minds, which do not seem able to adopt freely new ideas, the main cause of this delay is a trivial technicality: the need to prepare wooden forms*³

Flexible fabrics and textiles make excellent form-work for concrete^{4,5} The use of fabrics as formwork started initially with Felix Candela and Miquel Fisac^{6,7} The flexible nature of the fabric allows it to adjust its form in response to the hydrostatic pressure of the wet concrete the resulting in a very efficient use of material. Other characteristics of the fabrics provide additional benefits. The permeable nature of the fabric allows the excess water in the concrete to bleed, reducing the pressure on the formwork, trapped air is also able to escape, resulting in fewer surface blow holes and blemishes and hence a better quality of surface finish. A review of the benefits of permeable formwork has been prepared by Malone.⁸ Fabric formed concrete produces non-planar, often complex surfaces that are more visually interesting than flat surfaces. Thus textiles offer new possibilities for the expression and the pragmatic design of concrete. However, these admirable qualities may also be problematic. In construction accuracy and precision is essential. This paper presents a series of studies into the practical use of fabric formed concrete in the development, application and construction of architectural elements. These studies include the following aspects of construction and performance:

- connection and precision
- texture and surface
- the structural behaviour and design of form-active beams
- the construction of shell forms
- the relation between geometry and construction process.

These studies have been undertaken in the Architectural Research Workshop at the University of Edinburgh and in a series of live projects in the UK. Figure 1 shows the walls developed for the Royal Horticultural Show in Chelsea in 2009. These were constructed in collaboration with Alan Chandler from the University of East London and students from both institutions.



Figure 1: Fabric formed concrete panels at the RHS Chelsea 2009

An important aspect of the work is the development of technique through repeated prototyping. An overview of some of these projects is presented to demonstrate the range of elements that can be produced, the effect that different fabrics has on the surface finish of the concrete and the accuracy that can be achieved in components. It concludes that the use of fabrics as formwork presents a new approach to concrete design that offers considerable potential providing the design is based on a clear understanding of the material nature of both the concrete and textiles.

2 METHODOLOGY

The research has been undertaken through a series of workshops with students of architecture, empirical experimental research studies and live projects. The workshops encourage students, working in groups, to explore the potential of the technology and develop new construction forms through design, experimentation and repeated prototyping. Emphasis is placed on both the expressive qualities of the technology and pragmatic issues such as precision, repeatability of form, quality of finishes and sequence of construction. The research studies consider detailed aspects of performance such as structural behaviour and optimisation of form. The live projects are used to test the application of the techniques by interfacing with other disciplines and professions in real-time construction programmes. These effectively remove the research from the workshop and place it in the field. The range of components that can be produced using textiles as formwork is extensive; ranging from simple two-dimensional panels to complex three-dimensional wall constructions. An important aspect is to maintain the inherent simplicity of the process. Normally conventional concrete mixes are used, without additives or admixtures. A typical mix uses aggregates (10mm maximum size), sand and cement in relative proportions 10:5:4. The amount of water added is critical to ensure that the hydration of the cement will occur and the concrete has an appropriate degree of workability and can flow easily into the formwork. Typically the added water is 0.55 as a proportion of the weight of cement. Depending on the type of element the fabric is cut, shaped and then restrained by a frame. The fabric can be pre-tensioned to further control the geometry. As the concrete is placed into the formwork the fabric reacts, responding to the hydrostatic pressure, adopting a form-active surface as tension develops. During casting the some of the excess water in the mix will seep through the fabric. The rate of seepage is dependent on the permeability of the fabric. This has three benefits, firstly the hydrostatic pressure on the formwork is reduced, secondly entrapped air also escapes and thirdly the ratio of water to cement reduces and therefore increases the strength and durability of the concrete. During the casting procedure one can determine the degree of compaction and fill of the concrete by applying pressure through the fabric, not possible with conventional rigid formwork, which is largely a blind process once the concrete enters the formwork. After the concrete has hardened the fabric can be stripped. Most tightly woven fabrics can be removed easily. Fabrics with loose fibres or open weave may be more difficult to remove and may leave traces of fibre within the concrete. Very good and consistent results have been obtained with polypropylene geotextile fabrics.

3 EXAMPLES OF FABRIC FORMWORK ELEMENTS

The studies have considered a large variety of different elements and components. A selection of projects is presented to demonstrate the range of application and discuss some particular factors

3.1 Studies in texture and surface

Concrete is made from particles of varying sizes. The smallest particles are the cement grains, typically 15 microns on average. An effective mix is a well-graded blend of particle sizes. The finer cement particles migrate to the surface, defining the interface of the concrete with the formwork. The fineness of the cement is therefore able to replicate the texture of the fabric itself. The simplest fabric cast elements are panels. Fabric is stretched onto a frame, generally incorporating an upstand to contain the concrete around the perimeter. Concrete is cast directly onto the stretched fabric and finished to the level of the upstand. The weight of the panel causes the fabric to stretch and deform. The degree of deformation depends on the stiffness of the fabric, which can then be used to create additional surface undulation. Figure 2 demonstrates the fine surface grain that can be transferred from the fabric to the concrete.

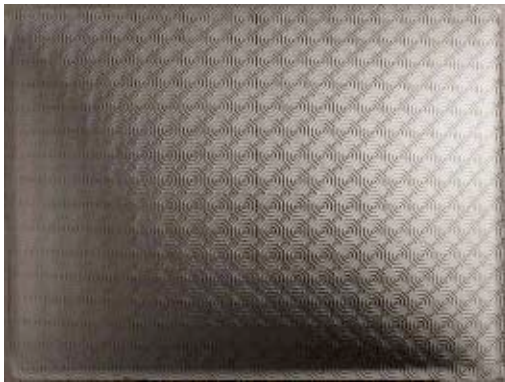


Figure 2 Fine surface texture



Figure 3 Smooth textured fabric

Figure 3 shows a panel using a smooth, coated fabric that creates a sheen on the surface of the panel the pattern has been produced by placing a series of steel rings under the fabric, imprinting the concentric circles into the concrete as the fabric deforms. The variety of effects and textures that can be produced simply by manipulating the type of fabric and patterns is almost limitless.



Figure 4 Rain-screen façade using concrete

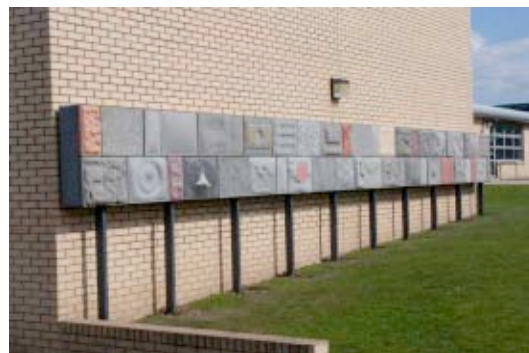


Figure 5 Rain-screen panels applied to school wall

In collaboration with a stone engineering contractor a demonstration wall was constructed to illustrate some of the variety of textures and surfaces possible using different textiles, figure 4. The panels were developed from the experience gained through a series of studies into surface and texture. The panels were attached to an aluminium framing system designed for thin stone cladding. The minimum thickness of the panels is 35 mm. The system is known as an open jointed rainscreen, systems of this type are used extensively in contemporary buildings. In a subsequent development the technique was applied to a project for a local primary school in Edinburgh. The pupils developed their own designs for the panels, figure 5.

3.2 Connection and precision

As the wet concrete is poured into the formwork the fabric responds by deforming, adopting a shape dictated by the effects of gravity, the degree of deformation is conditioned by the nature of the fabric, the hydrostatic pressure, the initial restraints applied by the formwork and pre-tension within the fabric. At present there exists little methodology to fully predict the exact geometry of a complex fabric cast form. In conventional formwork systems the use of rigid materials ensures consistent geometry throughout the element. In contemporary construction with its increasing emphasis on off-site operations and pre-fabrication the interfaces between components has become critical. At first consideration therefore it may seem that the self-organising nature of fabric formed concrete might be at odds with the need for precision. However the most important issue is to ensure accuracy where it is needed. Studies of the connections between fabric formed elements have been an integral part the research. In figures 4 and 5 the edge details between the panels was designed to ensure consistency in gap size and alignment between the panels although each panel was quite different.

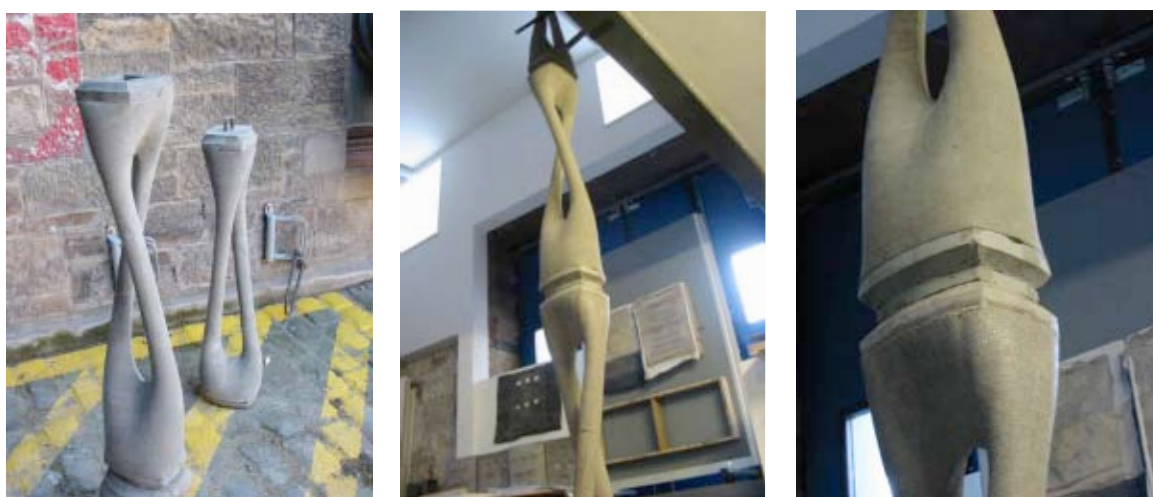


Figure 6 Accuracy, repeatability and connections

Figure 6 illustrates the development of a system for highly articulated columns consisting

of a series of twisted and perforated components. Each component has a slightly different form and uses a different fabric to create a variation in texture. The components connect to each other using an interlocking joint. The ends of each component were produced using a vacuum formed plastic insert into the formwork that ensured a high level of dimensional accuracy and fit. The components can be assembled in a variety of configurations.

Figure 7 shows a study of a column construction that utilises laser cut profiles to manipulate the surface, creating an undulating surface profile.



Figure 7 Undulated surface in column created by laser cut plywood ribs

The formwork consists of a cylinder of fabric stretched between two points. Normally uniform hydrostatic pressure will produce a column with a circular cross section. A sequence of vertical plywood profiles was positioned around the perimeter of the column to displace the fabric and allow the concrete to bulge in a controlled manner. The plywood strips were arranged in three rings around the column. The upper and lower rings were aligned vertically with each other whilst the middle ring was rotated relative to the other two. The result was an organic, articulated form that demonstrates the precise control over the deformation of the concrete that can be obtained.

3.3 Design of form-active beams

The geometry of a form-active structure follows the principal forces applied to it. Beams represent one of the most common structural elements in architecture and the most commonly occurring loading system (a load distributed uniformly along the length of the beam) for beams produces a parabolic distribution of bending moment; with a maximum at mid-span and diminishing to zero at the supports. The planar nature of conventional formwork generally simplifies the geometry to prismatic beams with a rectangular cross section, and therefore, non form-active shapes for which the formwork is relatively simple to construct but whose geometry is inherently inefficient. Constructing form-active beams using traditional methods is labour intensive and expensive. The use of fabrics to create a form-active geometry is quite straightforward. A study was undertaken to investigate the structural behaviour and design of form-active beams. Figure 8 illustrates the distribution of bending

moment in a uniformly loaded and figure 9 shows a fabric cast form-active beam.



Figure 8 Distribution of bending moment



Figure 9 Initial geometry of beam

The initial geometry of the beam is as shown in figure 9. The web of the beam follows the parabolic shape in figure 8. The steel reinforcement also follows the same profile. The projecting flange was developed to create an effective support at the bearings of the beam. Initial structural tests demonstrated that failure of the beam occurred at the bearings, where the flange met the web. The geometry of the cross section was gradually adapted through a series of successive modifications based on the analysis of structural tests. The final form that the process produced is shown in figure 10.

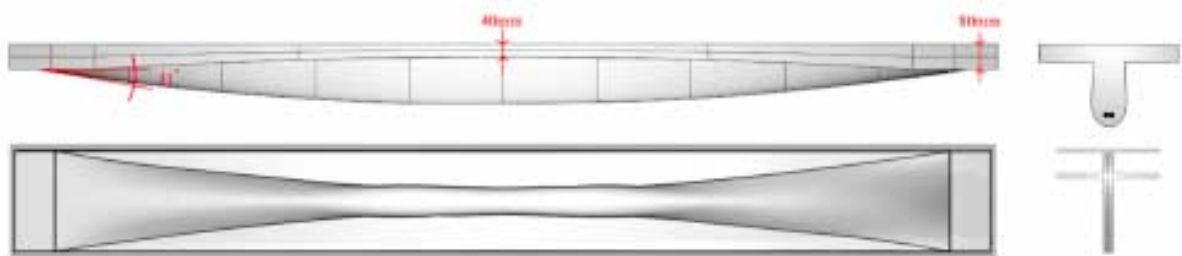


Figure 10 Final shape of concrete beam

The beam still follows the parabolic profile, but the major changes in geometry occur at the support. As the web gets shallower it also gets wider towards the supports. An upward curve has been added to the underside of the flange doubling the thickness of the flange towards the supports. These improvements in geometry have resulted in an increase in structural performance of the beam. By adjusting the geometry to place the concrete where it is most effective the failure mode of the beams changed and the load carrying capacity increased by over 35% for beams with the same amount of steel reinforcement⁹. As can be seen from figure 10 this mode of investigation through successive adaptation would have been difficult using conventional methods of formwork production. Each adaptation would have required significant labour in the construction. The use of fabric facilitated the repeated iterations of test, modify and make. A comparative study between of the embodied energy in the final design with a structurally equivalent prismatic beam indicated a reduction of 25- 40%⁹.

3.4 Shell structures

During the development of reinforced concrete in the early to mid 20th century one structural typology came to signify both the expressive and structural potential of the material, namely shell structures. Shell structures carry their load predominately by compressive stress. They are similar to traditional constructions such as vaults and domes but differ in a very particular way. Vaults and domes tend to be mass constructions and heavy. Angerer¹⁰, proposed a new classification to describe these structures, 'surface structures'. The primary difference being the thinness of the shell in relation to the span. Techniques such as graphic statics¹¹ and physical models allows the optimum geometry for efficient transmission of axial compressive stresses to be determined. Designers such as Torroja, Isler and Candela¹¹ used these techniques to produce very efficient and expressive structures. West¹² has constructed shells using fabrics as formwork. The fabric is suspended between supports and concrete applied directly. The fabric deforms to carry the concrete in tension resolving itself into the ideal catenary geometry. Once the concrete has set, the hardened form is inverted and the resulting shell has the optimum form for compressive forces. The most sensitive part of the process is during inversion of the form. A project at the University of Edinburgh also studied the construction of thin catenary shells using fabric, figure 11. The geometry was based on the Gaussian vault developed by Eladio Dieste¹¹. The overall form of the vault was described using two catenary curves of equal span but varying heights. Plywood profiles were made to follow these curves, which were then constructed into a frame. Fabric was stretched between the two profiles. Thin layers of concrete were applied directly to the fabric creating a series of compression curves spanning between the support points of varying heights between the two profiles. A preliminary study was undertaken to match the mix proportions with a variety of fabrics to determine best arrangement for adhesion of the concrete sloping surface of the fabric. A mix in relative proportions 4.5:2.5 coarse sand to cement was used. The shell has a thickness of 35 mm along both the principal curves that define the edge of the shell.

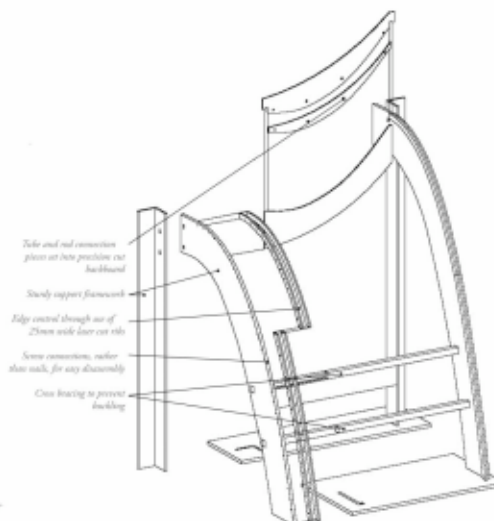


Figure 11 Concrete shell and formwork

3.5 Further studies in geometry and construction

In a recent project a group of students explored the complexity of form that could be produced using fabrics whilst maintaining an effective construction process. They sought to construct a formwork that could create a three-dimensional, highly perforated wall. A detailed series of construction studies investigated the effectiveness of filling a formwork with a complex arrangement of cavities. From these studies they determined parametric relationships concerning the position, shape and size of voids within the wall to fill the formwork effectively and minimise creases in the fabrics and surface defects in the concrete. The final wall, approximately 2.0 metres in height, was constructed as a single continuous formwork. Whereas previous projects has sought to produce assemblies of components by developing particular connections to join already cast pieces together this project sought to put emphasis on the monolithic qualities of concrete and thus all joints were formed within the fabric itself. The fabric was laid out and became the drawing on which the final design was developed, figure 11. Two layers of fabric were stitched together. A sequence of shapes was drawn on the fabric and then stitched through both layers. The shapes prevent concrete entering and create voids when the fabric is removed. The position and orientation of the shapes used information from the earlier parametric study to facilitate the placing and distribution of the concrete.



Figure 11 Layout and marking of formwork

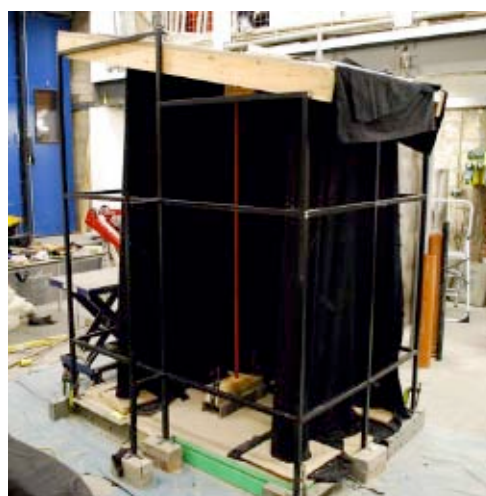


Figure 12 Fabric formwork

The fabric formwork was suspended from a sheet of plywood supported on a light steel frame, figure 12. Sleeves of the formwork were fed through holes in the plywood and used to fill the formwork. The fabric was then stretched and attached to a second sheet of plywood at the base of the frame. The formwork was arranged to describe an enclosed space, notionally with three sides. The group had previously developed techniques to create monolithic junctions in the fabric. The concrete was added in a carefully prepared sequence to ensure that all the branches were filled evenly. Reinforcement was added as the concrete was placed. The

concrete was placed in one continuous pour without interruption. The finished wall is shown in figure 13. There were very few blemishes or creases in the surface of the piece.



Figure 13 Images of complex form

4 CONCLUSIONS

The studies presented in this paper are a sample of the projects undertaken at the University of Edinburgh. They have been selected to demonstrate the range and variety of applications of fabrics as formwork for concrete. The use of fabrics, whilst not a universal panacea, offers benefits over conventional formwork techniques in a number of ways:

- Ease of construction
- A high quality of surface texture and appearance
- An almost limitless variety of finishes
- Accurate and precise in construction
- Efficient structural forms, such as shells and form-active beams
- Great complexity in geometry

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