STRUCTURE, FORM AND CONSTRUCTION

Fabric formwork for concrete

Abstract. This paper presents a summary of some recent research into optimised structural forms for concrete beams and columns, constructed using flexible woven fabrics as formwork. Fabric formwork is efficient in materials usage, improves the quality of the concrete and enables complex geometries that would otherwise be expensive to construct using rigid formwork. The paper provides a brief overview of the use of flexible formwork and presents summaries of two recent studies of structural elements: the development of a form-active efficient beam and a study of non-prismatic columns under axial load. The study of the beam indicated that the embodied energy could be reduced by over 30% when compared to comparable rectangular beam. The strength of columns is influenced considerably by shape with a significant increase or decrease in strength with non-prismatic tapered shapes compared to cylindrical prismatic columns with the same total volume of concrete. In both cases the complex three-dimensional shapes were simple and economic to construct.

Keywords. Concrete; form-work; textiles; fabric; beams; columns.

1. Introduction

The design of efficient structures requires articulating the form to maximise the use of materials and produce the most effective geometry. Often efficiency in materials using form may come at the cost of increased construction effort. Concrete is a material that, in particular, through its process of construction, suggests almost unlimited potential to create structures of any shape. In practice, however, the economic constraints lie not with the material in its liquid form but in the materials and skills available to manufacture the formwork.

Conventional formwork systems rely on flat, rigid materials, constructed by carpenters using timber or blacksmiths if metals are used. In both cases the materials and their associated fabrication processes generally lead to
simple, prismatic and orthogonal geometries. As Pier Luigi Nervi (1956) noted:

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, PL Nervi 1956.

Optimised structural geometries are generally non-prismatic, have complex cross-sections and are expensive to construct using these conventional methods. In recent years these have been considerable research and interest in the use of flexible formworks using textile fabrics to restrain and shape concrete elements. When used to thinking in terms of apparently robust and rigid formwork constructed using plywood or other materials it may appear counter-intuitive to use apparently flimsy materials such as textiles to constrain heavy, wet concrete however practice has shown that it is highly effective. It deforms under pressure to provide the most efficient shape to sustain the weight of the concrete. Furthermore, the permeable nature of woven textiles allows the passage of trapped air and excess water and helps reduce the water-cement ratio of the concrete, leading to improved strength and fewer defects.

For over ten years there has been sustained study into the use of fabric as formwork at the University of Edinburgh in both architectural and structural applications. This paper presents a brief summary of some recent research into optimised structural forms for beams and columns. The optimum geometry of a simply supported beam was developed through an iterative process of repeated test and analysis of various cross-sections and shape. The final geometry of the beam was a non-prismatic Tee-section for which the web varies in depth according to the bending moment and the flange varied in thickness according to the shear forces. Although there is great complexity in the geometry, the formwork consisted of a single sheet of textile and a flat sheet of plywood and was very simple to construct. The beam has a reduction in embodied energy of approximately 30% compared to a structurally comparable beam using conventional formwork. Non-prismatic columns are simple to construct using fabric formwork. A study of the effect of geometry on the axial load capacity of concrete columns was undertaken by comparing the strength of tapered (concave) and bulged (convex) columns with cylindrical prismatic columns. The same total volume of concrete was used in all columns and it has been shown that the strength of column is con-
siderably influenced by shape and that significant improvements can be obtained with no increase in construction cost.

Fabric formwork can be perceived as a disruptive technology with considerable potential for structural and architecturally expressive elements.

2. Overview of research into fabric formwork

At present fabric formwork is not used widely in buildings and structures; there are however a number of established applications in engineering and marine constructions such as coastal erosion, marine foundations and pile jacketing, applications where the formwork may have to adapt to irregular surfaces or access may be difficult, (Abdelgader et al 2008).

Despite the limited applications in buildings, fabric formwork actually has a comparatively long history. A review of the history of fabric formed concrete has been presented by Veenendaal (2011). Gustav Lilienthal patented a system of fire proof construction for floors using fabric draped between timber floor beams in 1899. The Irish engineer James Waller, (Conlon 2012), developed the Ctesiphon roof system, first used in 1941, as an efficient method of constructing single storey sheds. The system used Hessian fabric to produce corrugated shells only 7-9 cm in thickness spanning over 20 metres. In Spain Miguel Fisac developed an expressive form of construction to produce highly textured and articulated cladding panels by controlling the deformation of the fabric during casting, (García Carbonero 2003).

Over the last 20 years or so there has been a major growth in both research and application of fabric formwork, led initially by the inspiring and creative work of Prof. Mark West of the University of Manitoba and the foundation of the Centre for Architecture and Structural Technology. Research is now active and spreading, the 2nd International Conference on Flexible Formwork in 2012 had contributions from nearly 20 countries, on topics ranging from case studies, tectonics, structural behavior, modeling and form-finding, (Orr et al 2012).

2.2 ADVANTAGES OF FABRIC FORMWORK

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

- **Formwork is lighter and easier to fabricate than conventional rigid techniques.** All of the projects reported in this paper were fabricated by students.
- **The fabric deforms to the optimum geometry.** The fabric can carry only the wet concrete by generating axial tensile forces in response to the hydrostatic pressure of the wet concrete.
• **Complex forms can be produced.** By careful shaping of the fabrics optimised structural forms can be developed that would otherwise be very expensive with conventional systems.

• **The permeability of the fabric improves the quality of the concrete.** The excess water in the concrete can escape during casting, reducing the pressure on the formwork and the water-cement ratio, which increases the compressive strength. Trapped air is also able to escape, resulting in fewer surface defects and hence a better quality of surface finish.

• **Large variety of surface finishes possible.** An almost limitless variety of finishes that can improve the visual quality of the finished object considerably can be produced. (Figure 1).

![Figure 1 Rain-screen cladding system showing a variety of surfaces and textures](image)

Many types of fabric can be used as formwork, often woven geotextiles have been used as these are strong, have good tear resistance and do not absorb water.

**2.3 STUDIES OF FABRIC FORMWORK AT THE UNIVERSITY OF EDINBURGH**

Research at the University of Edinburgh is concerned with understanding the key factors that influence the effective application of fabric formwork in both architectural and structural application. The technology is seen as ‘Disruptive’, first defined by Christensen (1997). It has developed from non-traditional sources and challenges the accepted paradigm of existing practice, namely rigid formwork. The research methodology encompasses both architectural and structural applications. In the former an innovative design studio was developed that has been running for ten years in which postgraduate students design, develop and construct full-scale architectural elements, through a process of repeated prototyping and production. Over six weeks they quickly become experienced in formwork construction assembly and
casting concrete. Figure 2 illustrates two studies into complexity of form: an over-lapping wave form and a highly complex perforated frame.

![Figure 2 Construction studies of concrete wave forms and complex frames](image)

The studies have also included various forms of shells, Figure 3

![Figure 3 Studies of Hyperbolic and Gaussian Shells](image)

Other studies, in collaboration with the School of Engineering focus more directly on the design and behaviour of optimised structural components such as beams and columns. Sections 3 and 4 present summaries of two recent studies into shape optimised beams and columns.

3. **Studies of form active beams**

The geometry of a form-active structure follows the principal forces applied to it and consequently material is more uniformly stressed and therefore in-
herently more efficient. The planar nature of conventional formwork generally mitigates against form-active shapes and results in a simplified geometry of prismatic beams with a rectangular cross section. Constructing form-active beams using traditional methods is therefore labour intensive and expensive. There has been some research into the structural behaviour of form active beams using textile formwork. Hashemain 2012 undertook a study of beams with a profile shaped to follow the bending moment diagram. He reported failures at the support, which were improved by developing a range of more robust anchorage details. Orr 2012, studied the behaviour of double Tee section beams using fabric formwork. In these beams the rectangular flange of cross-section was much larger in proportion to the section of the web and the behaviour is closer to that of a stiffened slab than form-active beam. A different approach was adopted in the studies at Edinburgh. The studies recognised the ease with which changes in geometry could be made in the construction process, enabling an iterative and reflective process of experimentation, analysis and geometric modification to be developed. The beam comprised a flange and a curved web, the flange occupied a much smaller proportion of the cross-section than Orr. Figure 4 illustrates the initial geometry and final geometry of the beams.

![Figure 4 Initial (left) and final (right) geometry of the beams](image)

The flange was included to help with both practical and aesthetic issues:

- **Bearing and anchorage.** The web terminates immediately before the bearing point. In practice this would simplify construction and the width of the flange allows sufficient space for the anchorage of the reinforcement.
- **Aesthetic.** The detail allows the full visual expression of the curved geometry of the web and hence demonstrates the intended structural behaviour.

A total of 14 beams were tested in a programme of progressive modification to the details and geometry. More information is given in Lee 2011.
The construction of the beams was undertaken on a specially designed steel frame. A plywood sheet was used to form the flange of the beams. The web of the beam was formed by cutting a slot in the plywood and carefully positioning a woven geotextile membrane into the slot to drape below the flange. The precise shape of the web was determined by clamping plywood profiles either side of the membrane. The reinforcement was curved to follow the parabolic profile of the web. Short perpendicular bars were welded at the ends to provide anchorage. A light mesh was incorporated into the flange, but no shear reinforcement was used, see Figure 5.

![Formwork for beam and finished beam with initial profile](image)

### 3.1 STRUCTRAL TESTING AND RESULTS

The beams were tested over a simply supported span of 3.02 metres with a six point loading arrangement to generate equivalent moments to a uniform distributed load. In the initial tests the beams failed through a combination of anchorage crushing and shear. Thus the full flexural capacity of the beams was not being achieved. The original geometry of the beam was modified through six iterations, these include:

- **Improvements in the detail of the anchorage of the bars.**
- **Changing the angle of main reinforcement at the anchorage point.** Increasing the angle reduced the compressive force in the flange at the bearing and increased the failure load.
- **Increasing the percentage of reinforcement.**
- **Developing a tapered flange detail.** Increasing the thickness of the flange locally at the reaction point

In the final form the failure mode changed from anchorage and shear to that of flexure, with the steel reinforcement yielding at mid-span. The final modification was a major change to the geometry of the web. In the original beam there is a concentration of material at the mid-span, where the web is both at it deepest and it’s widest, Figure 5. However this extra material
around the reinforcement is unnecessary. Close to the support the web is at both its narrowest and shallowest. The final change allowed a redistribution of the material within the web to maintain the same variation in depth but the width altered from narrow at mid-span to wide as it approaches the support. In addition the flange thickness was increased from 40 mm at mid-span to 80 mm at the supports, Figure 6.

The final geometry is rather complex but was very simple to construct and consisted of a flat sheet of plywood with cut out following the junction of the flange and the web. The change in thickness of the flange was produced simply by curving the plywood using timber wedges. Using a single sheet of geotextile fabric and simply positioning and attaching it carefully and precisely to the plywood, it naturally deformed to the required shape when the wet concrete was poured. The embodied energy of the final design was calculated and compared to conventional beam of equivalent strength and showed a reduction of approximately 30 %, (Lee 2011).

A further series of 4 tests were undertaken on the same configuration to study and verify the structural performance. The same form-work was used. The steel mesh was replaced by use of distributed polypropylene fibres, (Strux90/40). The results are summarised in table 1. All four beams failed in flexure, ductile failure with steel yielding. The ductile failure can be seen in the load-deformation results for the last cycle of load, Figure 7. The results also highlight an important aspect in using fabric formwork. The method of positioning the main reinforcement at the centre of the beam was changed between beams 1-2 and beams 3-4. In the former the reinforcement was placed using spacers placed on the fabric itself, guaranteeing a minimum cover in conventional practice, as the textile deformed to receive the wet concrete the effective depth changed slightly. In the latter (beams 3 and 4) the reinforcement was suspended from the top of the formwork using wires and this resulted in more consistent positioning, (Lee and Pedreschi, 2015)
4. Studies of non-prismatic columns

A second study considered the use of fabric formwork in the construction of non-prismatic columns. Similarly to the design of form-active beams, non-prismatic columns are more difficult to construct using conventional rigid formworks. Using fabrics allows a great variety of complex geometries. These have great architectural potential and have been studied extensively at the University of Edinburgh, (Pedreschi 2013). A series of ten non-prismatic columns was constructed. Five configurations of column were considered: two with concave profiles and two with convex profile and a prismatic cylindrical column. The columns were designed to have the same total volume of concrete to consider if improvements in axial strength could be obtained by altering the geometry, Figure 8.
A short review of some cylindrical columns in recent buildings indicated that the slenderness ratio typically ranged from 28 – 40. A slenderness ratio of 40 was chosen for the prismatic column from which the non-prismatic columns were developed. The formwork for the columns used a woven polypropylene textile, intended for non-structural applications such as lining for upholstery. The convex and concave profiles were traced onto 10 mm plywood pieces, used to form side clamps for the fabric. The fabric was carefully set out and stapled to the plywood clamps, two sets of clamps were used for each column, arranged at 180 degrees to each other. The clamps define the diameter of the column throughout its length and are also used to accurately determine its height. As concrete is poured into the formwork the hydrostatic pressure causes the formwork to develop a circular cross-section, the diameter of which is determined by the position and shape of the clamps. The columns were assembled in a steel frame and attached to a stiff plywood top and base to ensure vertical alignment. The frame was designed to accommodate five columns, which were then cast simultaneously. Reinforcement was not included but is the subject of a subsequent study (Pedreschi 2015). The columns are cast by pouring concrete through a series of holes in the plywood top plate. It is interesting to note that the formwork does not actually need the support at the top of the frame as the formwork fills from the bottom. As the formwork fills the pressure defines the finished shape and stabiles the form. The frame however helps control the overall accuracy and vertical alignment.

4.1 STRUCTURAL TESTING OF COLUMNS AND RESULTS

The columns were tested in an Avery Universal Test Machine. The ends of the columns were capped and levelled using rapid setting plaster. Demec
points were placed around the perimeter at 4 positions at mid height. A small increment of load was applied and the strains recorded. Each column was adjusted slightly to obtain as near as practical uniform strain. The column was then tested to failure. No buckling was observed in any of the tests. The concave columns generally failed at mid-height, initiated by vertical cracking due to transverse tensile strains. The convex columns tended to fail close to the loading plate. The results are summarised in table 2. Unfortunately column 1 was damaged in transit to the test rig and not tested.

Table 2 Summary of tests on columns

<table>
<thead>
<tr>
<th>Column No.</th>
<th>Shape</th>
<th>Difference between Max - min. diameter mm</th>
<th>Compressive strength N/mm²</th>
<th>Failure load kN</th>
<th>Failure load/Compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 2.</td>
<td>Concave</td>
<td>25 - 42.6</td>
<td>N/A</td>
<td>214.5</td>
<td>N/A 5.04</td>
</tr>
<tr>
<td>3. 4.</td>
<td>Concave</td>
<td>10 34.3 - 40.6</td>
<td>213</td>
<td>219</td>
<td>6.21 5.39</td>
</tr>
<tr>
<td>5. 6.</td>
<td>Prismatic</td>
<td>0 42 - 43.5</td>
<td>144</td>
<td>216</td>
<td>3.42 4.96</td>
</tr>
<tr>
<td>7. 8.</td>
<td>Convex</td>
<td>10 42 - 43.5</td>
<td>135</td>
<td>188</td>
<td>3.21 4.32</td>
</tr>
<tr>
<td>9. 10.</td>
<td>Convex</td>
<td>25 38.4 - 42.6</td>
<td>77</td>
<td>102</td>
<td>2.01 2.39</td>
</tr>
</tbody>
</table>

The last column of the table compares the failure load corrected for the compressive strength of the concrete in each case. The results indicate a clear trend. Convex shaped columns, bulging at mid-height, are significantly weaker than either the cylindrical or concave columns. The concave columns tend to be stronger than the cylindrical columns. This increase in strength comes at no additional cost of material. A further series of tests on 30 columns with differing geometries and including reinforcement has recently been completed, (Pedreschi 2015). These tests include the use of Digital Image Correlation techniques and preliminary analysis indicates that higher failure loads in the concave columns are the result of a reduction in transverse tensile strains.
5. Summary and conclusions

The paper has presented a brief survey of some recent work on the use of flexible fabrics as formwork for concrete elements. It demonstrates that the technique is both practical and effective. It provides the opportunity to create complex structural forms such as beams and columns in concrete that are more efficient than conventional prismatic and orthogonal shapes yet are also more simple and efficient to construct.

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References


