FABRIC-FORMED CONCRETE STRUCTURES

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ABSTRACT
A new construction method replacing rigid formwork panels with a flexible textile membrane that deflects under the dead weight of wet concrete, provides numerous advantages and opportunities for architecture, engineering, and construction technology in both advanced and basic building economies.

Inexpensive formwork fabrics provide the options of sacrificial or reusable formworks in both precast and cast-in-place applications. Methods have been developed for fabric-cast foundations, walls, columns, capitals, slabs, and beams.

Permeable membranes allow air bubbles and excess mix water to bleed out, producing a flawless, cement-rich finish and a stronger and more durable “case hardened” concrete.

Structurally efficient variable section members are easily formed, reducing dead weight and material expenses. Steel-free concrete structures are envisioned through the use of three dimensional compression geometries formed through a simple inversion of funicular curves.

The paper introduces this new technology, citing current work and applications as well as future research opportunities.

Keywords: fabric formwork, flexible formwork, compression shells, variable section members

INTRODUCTION

Fabric formwork has been used in the field of geo-textiles since the mid-1960's to form concrete on the ground and underwater. More recently, a small number of architects and builders have begun using flexible fabric formworks for cast-in-place foundations, and cast-in-place and precast columns and walls in Canada, Japan, and Spain [1] [2] [3] [4]. Full scale demonstration projects of fabric-cast beams and slabs have also been accomplished [5] [6] [7] [8]. Other applications currently under development include formworks for precast concrete compression shells, and steel-free concrete infrastructure. The world's first research laboratory for fabric formwork technology is currently under construction at the University of Manitoba in Winnipeg Manitoba, Canada. The establishment of this laboratory is forging research partnerships between practicing and academic architects, engineers, mathematicians, and various sectors of the construction industry in North America.

This is a new technology with many possible applications and avenues for future research. It is not the intention of this paper to report detailed findings in specific areas – instead, it presents a general introduction to this field through descriptions of various flexible formwork strategies, and outlines several opportunities for future research projects.

The origins of traditional practice

Concrete has been formed in rigid molds since its invention in antiquity. Rigid wood or steel formwork panels have been used since the mid-1800's, giving us a 'vocabulary' of structural form that relies primarily on rectangular prismatic solids. While traditional rectangular forms are simple to construct from rigid formwork panels, the structural members they produce will tend to use more material and carry more dead weight than a properly designed variable section member. By replacing rigid wood or steel forms with a flexible fabric membrane that is allowed to deflect under the weight of the concrete it contains, curved geometries and variable section members become extremely easy to form.

Engineering practice normally considers deflection only as something to be avoided. The deeper truth of deflection curves, however, lies in their inherent structural 'intelligence'; the curves of a moment diagram, or funicular shell geometries are of this more intelligent and efficient order, and are among the geometries of choice for light weight or long span structures.

Historically, the calculations for these more sophisticated geometries were very time consuming, or impossible to perform. The limitations of the slide rule demanded simple geometries, favoring those shapes whose areas could be calculated by the multiplication of two numbers. For example, the great Italian engineer Piere Luigi Nervi could not calculate his famous light weight concrete structures. Instead, he designed these works using scaled physical models equipped with strain gauges.

The replacement of the slide rule by the computer has given us a powerful analytical and design tool that allow, for the first time, the calculation of complex, and more efficient, structural geometries. Concurrent with the introduction of the computer to engineering practice, the development of inexpensive yet powerful polyolefin textiles, makes possible the efficient physical production of these more efficient structural shapes. These two recent advances make it possible to re-think both the design and construction of reinforced concrete structures. The use of flexible, fabric formworks presents a new and fundamentally different approach to construction with several significant advantages.

ADVANTAGES OFFERED BY FLEXIBLE FABRIC FORMWORKS

By combining the formwork's flexibility and the concrete's plasticity we are offered several advantageous effects:

1. The provision of an inexpensive, extremely light weight, and globally available formwork material in place of wood (which is generally hard to find in building economies that rely on reinforced concrete construction).
2. A new and unprecedented level of refinement in the surface finish and texture of cast concrete.
3. The automatic production of stronger and less permeable concrete surfaces.
4. The creation of a new class of highly efficient, complex, yet easily formed structural shapes. based on pure tension geometries, and their inversion as pure compression geometries.
5. A new 'language' of architectural form, providing a radically different understanding of what reinforced concrete architecture can be like.

The first four points are discussed in more detail below:

1. Light weight, low cost formwork structures

Forming a heavy plastic material like concrete into rectangular prismatic solids requires a great deal of effort – indeed, the difficulty of limiting the deflection of rigid formworks accounts for the vast majority of their structure. Take, for example, the formwork for a concrete column: By replacing rigid panels with a thin textile tension membrane, the vast majority of material normally required to restrain the wet concrete is eliminated. The only exterior support this membrane requires is scaffolding to hold the top of the form in position (the shoring for the beams and slab above can serve this purpose). No other restrains are needed to support the formwork.

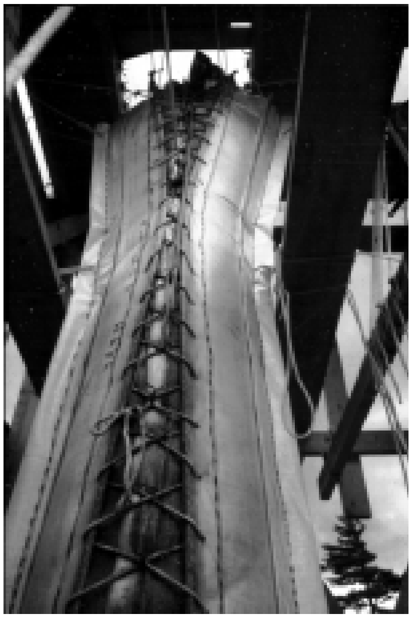

Figure 1. Woven polyethylene column formwork filled with concrete.

The light-weight nature of fabric formwork is illustrated in the example of Figure 1. This particular column formwork is designed to be reusable, and to provide variations in column diameter from .32M to .65M, and variations in height up to 4M (designs for greater heights and diameters also exist). In the case illustrated, the column height is 3.9M and the variations in diameter (between .32M and .48M) are for architectural purposes only. The total weight of the fabric and ropes in this form is only 7.5 kg. Fixed dimension fabric formwork designs for a column of equivalent size can be as light 2 kg.

This extreme reduction in the weight of the formwork itself opens up several significant opportunities, including savings in material, storage, and transportation costs. These formworks are light and compact enough to be economically shipped from one location to another around the world.

The Polyolifin fabrics best suited to most applications are very inexpensive and available world-wide. In North America these fabrics cost less than \$1 (U.S.) per M^2. Concrete will not adhere to the surface of these fabrics, so they do not require release agents of any kind. They are reusable many times over. Their low material cost also makes them ideal for sacrificial formwork.

The use of fabric formworks does not require a high level of technological development. The fabrication of these forms require only the ability too cut and sew fabric tarps to simple patterns. In its most basic form, the technology required to install and use these forms requires no more than the ability to tie knots - no mechanical devices are needed. However, extensions and elaborations of the technology's basic principles can lead to highly sophisticated applications and structural geometries which will be described in more detail below. In either case, the fundamental advantages offered by flexible formworks are the result of their essential simplicity. Use of fabric formwork presents particular advantages in building cultures and economies where wood and/or steel are difficult or expensive to obtain.

The simplicity with which these forms are constructed can be illustrated by the Figure 1. column formwork referred to above: This formwork is made of two rectangular panels of inexpensive, woven, high density polyethelene. The two halves are laced together using 7mm diameter rope, creating a hollow mold. No other hardware is required except two pairs of light steel bars inserted within edge hems sewn in the panels. Typically these are simply reinforcing bars found on the construction site. These bars act as splines used to seat the lacings against the fabric, and to evenly distribute the tension forces of the lacings to the fabric panels. The ropes used in the lacings penetrate the fabric panels by passing through the woven structure of the fabric without disrupting the structural integrity of the membrane. No grommets are required. The bottom of the formwork is tied to a cylindrical footing, while the top is pre-tensioned upwards by hand. When loaded, the horizontal tapes in the weave do nearly all the work of restraining the wet concrete. These forms have proven to be very robust, and can be shaken or vibrated quite vigorously while the concrete is still wet. The mild vertical pre-tensioning is sufficient to make the formwork latteraly self stabilizing.

Flexible formworks have one significant weakness: since they lack rigidity, they cannot protect the concrete from lateral loads while the concrete is weak. Until the concrete has developed sufficient strength to withstand lateral forces, the formwork must not be handled at all, or the newly set concrete may become cracked. Barricades should be placed around recently poured members to avoid damage.

2, 3. Improved surface finish; Improved surface compaction, strength.

One of the most dramatic advantages of using fabric formworks is the great improvement they require in the quality and density of the concrete's surface. When uncoated permeable fabrics are used as formwork membranes, these fabrics act as filters that allow air bubbles and excess mix water to bleed out. This leaves an immaculate cement-rich paste the surface. This loss of water can also significantly improve the water-cement ratio at the surface of the member, providing a denser and significantly stronger 'case hardened' concrete. How far this case hardening effect penetrates into the section of the concrete will depend on the fabric used. [9] [10] [11]

Vibration and compaction of the concrete can be obtained by either internal or external vibration. A perfect surface finish can be obtained from a permeable form by patting the outside of the formwork by hand. This kind of external vibration helps the flow of excess mix water through the formwork membrane. Even relatively low-slump concrete mixes will obtain immaculate surfaces by this method. External vibration is not recommended for 'plastisized' concrete mix designs using water reducing agents. Our experience indicates that plastisized concretes should be placed without external vibration to avoid uneven surface colouration.

Traditional cast concrete has earned a reputation as a 'hard' and even 'brutal' material. Fabric formwork reawakens concrete to its fluid origins, transforming cast concrete into a 'soft' material that invites touch, thus introducing an entirely new aesthetic and sculptural vocabulary for concrete that awaits exploration by architects and builders. The surface of fabric-cast concrete does not require further work after the forms have been stripped. In this way the beauty of fabric-cast surfaces can reduce construction costs by eliminating the need to cover or otherwise alter the surface of an exposed concrete structure for aesthetic purposes.

4. High efficiency structural members

As outlined in the Introduction above, flexible fabric formworks are particularly suited to the economical production of variable section members. The production of structural members with efficient structurally defined curves, provides concrete only where it is needed. In this respect the flexibility of fabric formworks serves to emulate the geometry of certain biological structures that provide structural material in response to stress concentrations. Reductions in the amount of concrete required can be quite significant. In certain cases these savings in material and weight are estimated to be as high as 40%.

There are two basic strategies for achieving variable section members:

4.1 Cast-in-place variable section members

Cast-in-place applications use the dead-weight of the wet concrete to produce deflection geometries that are structurally advantageous.

A one-way ribbed slab can be formed by allowing deflections in a formwork membrane placed over standard shoring beams (Figure 2a), producing the transverse section shown in Figure 2b. This structural section presents significant savings in material and dead weight compared with a standard rectangular section of the same depth. The effective depth of this slab is achieved by tying the 'bottom' reinforcing steel to the fabric formwork on standard 'chairs,' so that it is carried down withthe formwork as it deflects, maintaining a standard cover of concrete.The ‘top steel’, is supported on standard ‘chairs’ placed directly above the shoring beams (Figure 3). the formwork as it deflects, maintaining a standard cover of concrete.The ‘top steel’, is supported on standard ‘chairs’ placed directly above the shoring beams (Figure 3).

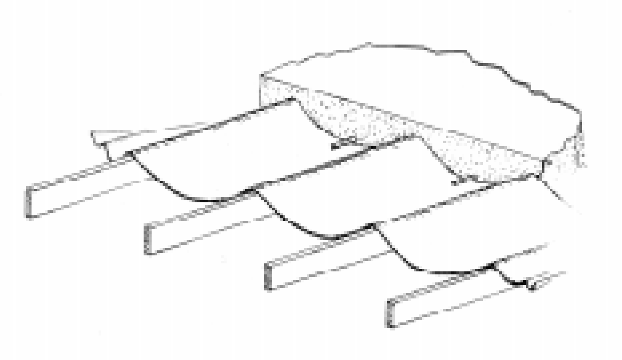

Figure 2a. Schematic drawing of fabric formwork allowed to deflect between shoring beams.

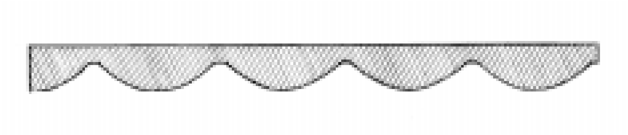

Figure 2b. Schematic structural section of fabric-formed ribbed one-way slab created by the Figure 2a formwork.

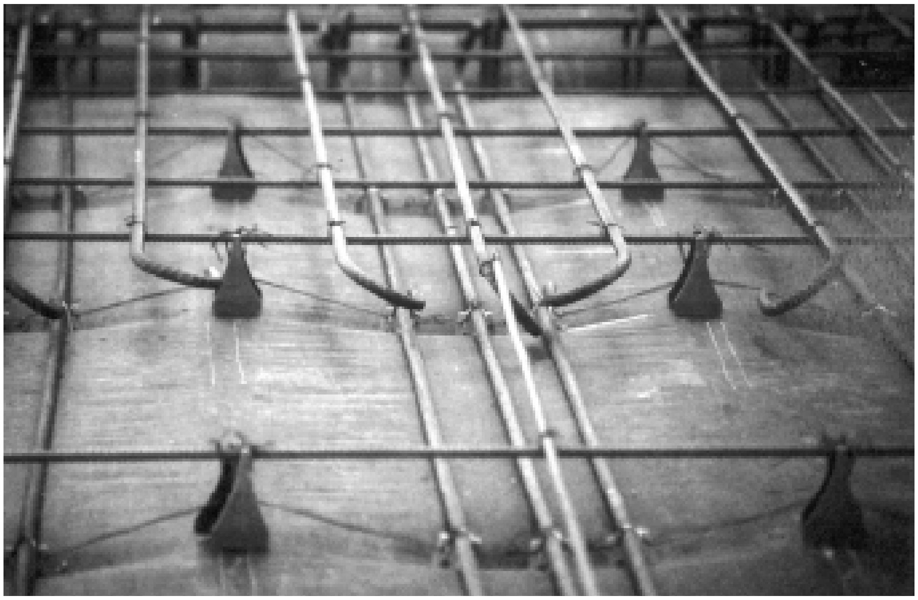

Figure 3. Photograph of top and bottom reinforcing steel placed on a ribbed one-way slab formwork: top steel supported on shoring beams, and bottom steel tied to fabric membrane.

Several configurations using this strategy are possible, including formwork that will simultaneously form a ribbed one-way slab, along with its supporting beam, illustrated by the model shown in Figure 4 and the drawing in Figure 5. Figure 6 and Figure 7 illustrates a full-scale test of formwork using this strategy. This double cantilever, one-way ribbed slab was formed simultaneously with its two beams and four columns. The formwork was made with three flat sheets of fabric on standard shoring beams.

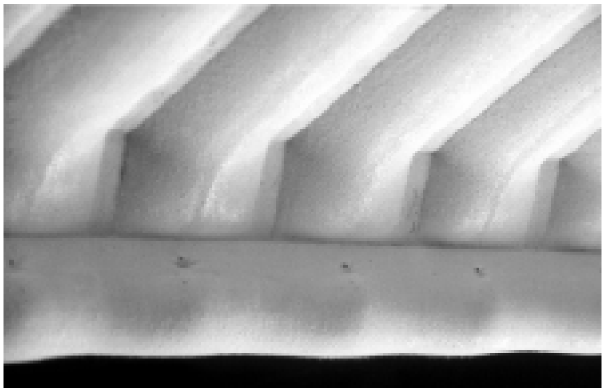

Figure 4. Model showing ribbed slab and its supporting beam formed from a single flat sheet of fabric.

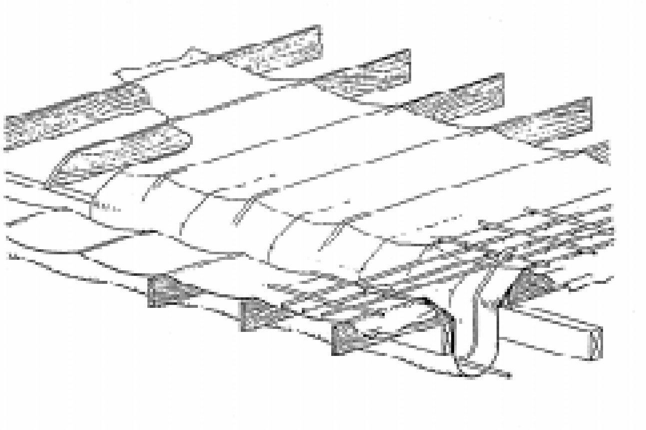

Figure 5. Schematic drawing showing shoring beams and fabric membrane used to form integral slab and beam.

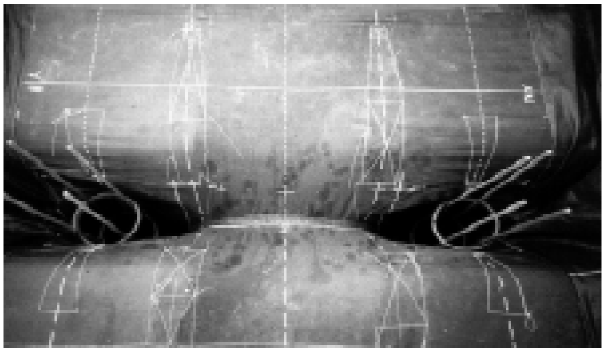

Figure 6. Photograph of slab-beam-column intersection in full scale test slab.

Figure 7. Photograph from below of one-way slab with integral beams and columns.

Variable section, cast-in-place beams may also be formed using a flat rectangular sheet of fabric. Curving the horizontal boundary of this rectangle results in a form for casting simple variable section beams (figure 8). Greater geometric precision can be obtained by 'tailoring' the fabric formwork by sewing a curved seam along the bottom of the form. Further refinements in the structural section may be obtained by a horizontal and/or vertical pre-tensioning of the formwork, thus reducing the horizontal deflection that results when the forms are loaded with concrete.

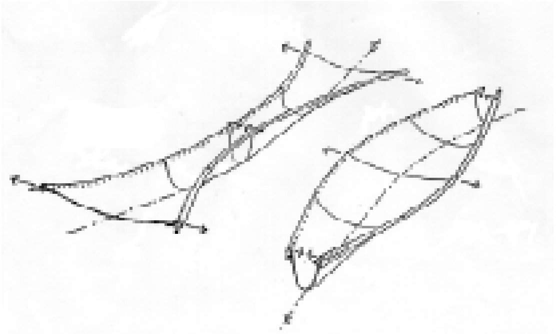

Figure 8. A simple flat rectangular sheet of fabric can be used to form variable section beams.

4.2 Precast (inverted) variable section members

Another method of producing efficient variable section members takes advantage of the geometric inversion of pure tension geometries to cast structural members with pure compression shapes.

The use of concrete in pure compression structures invokes the most ancient uses of concrete as well as recent research into the actual behaviour and failure modes of concrete slabs. [12] [13] [14] The significant economies inherent to steel-free and non-reinforced concrete structures have made this an active area of research. The advantages of eliminating steel reinforcement from concrete structures range from material savings (particularly important in construction economies where steel is relatively expensive), to service life issues for concrete infrastructure in corrosive environments.

The first step in producing a mold for precasting compression shapes is to strategically load a flexible membrane with concrete. The tension strains in the formwork fabric caused by this initial loading provide the three dimensional funicular curves required for the precasting mold. This initial cast is then turned upside-down, presenting us with a curved funicular shell form used to produce members that will resist the initial loading pattern (now inverted) through pure compression (figure 9). Specific funicular deflection patterns can be produced through a variety of techniques, including variations in fabric prestress levels and alterations in the initial loading regime.

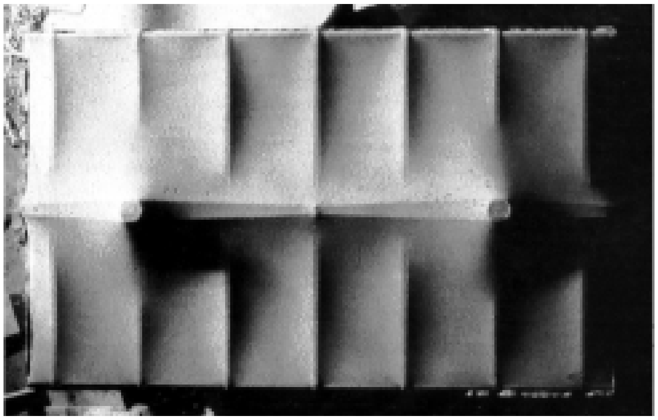

Figure 9. Model, showing underside of precast slab with integral variable section beams and compression shell/funicular arch geometries.

This strategy can be used to form compression shell molds with a wide variety of boundary conditions. It may also be used to form floor slabs whose lower surface follows compression vault shapes, thereby reducing the weight and material requirements of the slab, and carrying its own dead weight in pure compression. The horizontal thrust produced by these vaults or shells would be taken by end-bay edge beams restrained by buttresses or tension ties.

CURRENT WORK AND FUTURE RESEARCH

At this stage of our research many questions remain unanswered. There are also many applications for this technology that have not yet been identified. Although full scale, fabric-formed columns, walls, and foundations are being built in North America and Japan, the current use of this technology does not yet address the potential structural efficiencies this technology holds. It also does not address its potential for use in so-called 'developing' building economies and building cultures, nor in those building economies and cultures that simply lack wood. Full-scale tests of many formwork designs have yet to be done. Structural tests of fabric-formed, variable section beams and slabs also need to be done. Software to support flexible formwork design and the structural design of complex variable section members needs to be developed.

The Centre for Architectural Structures and Technology (C.A.S.T.) will be the first research laboratory dedicated to fabric-formed concrete. The construction of our new laboratory building will be completed by the Fall of 2001. The work of C.A.S.T. simultaneously embraces questions of structural engineering, architectural design and construction technology. We are actively searching for collaborators and partners interested in this work.

END NOTES:

[1] A fabric formwork system for strip footings, point footings, and foundation curb walls has been developed by Rick Fearn of Fastfoot Industries in Vancouver British Columbia, Canada: www.fastfoot.com

[2] The first known fabric formed columns are by the author and his students, Carleton University, Ottawa, Ontario, Canada, 1989. The first known structural use of fabric-formed columns is by the author in Winnipeg, Manitoba,1998. [5] [6] [7] [8]

[3] The first know structural use of cast-in-place, fabric-formed walls is by Japanese architect Kenzo Unno who has developed a very elegant and light weight formwork system. Unno has also used cast-in-place fabric-formed columns of his own design. [1] [2] [3]

[4] The first structural use of pre-cast fabric-formed wall panels was by the Spanish architect Miguel Fisac in the early to late 1970's. [4]

[5] The author has demonstrated the construction of full scale fabric-formed slabs and beams at Carleton University, Ottawa, Ontario, Canada. [5] [6] [7] [8]

[6] Research describing the increased strength of fabric-formed concrete has been done in the field of geo textiles where fabric formwork has been used since the mid-Nineteen Sixties to cast rivetments, cooling pond liners, and underwater pile jackets. [9] [10] [11]

[7] Recent research in the structural behaviour of reinforced concrete bridge decks confirms an internal arching action gives these slabs far greater strength than slabs in pure bending. This work has led to the design and construction of steel-free concrete bridge decks in Canada. [12] [13] [14]

[8] The reinforced brick funicular vaults of the late Uruguayan engineer Eladio Dieste are particularly instructive in this regard. Fabric formed models following Dieste's Gausian compression vaults have been produced by graduate architecture students at the University of Manitoba's Centre for Architectural Structures and Technology (C.A.S.T.).

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