Fabric-formed concrete: A novel method for forming concrete structures

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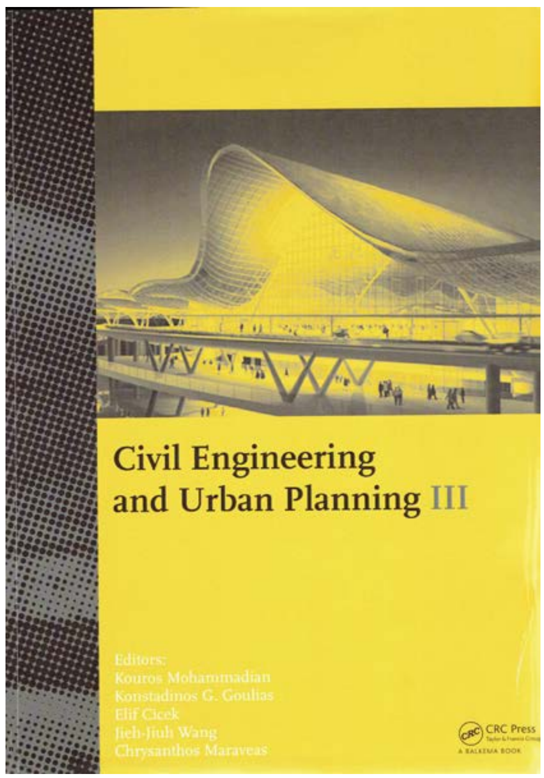

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Fabric-formed concrete: A novel method for forming concrete structures

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ABSTRACT: Concrete members have traditionally been cast using a rigid formwork. However, casting concrete in a flexible formwork may in fact be used nearly anywhere a rigid formwork is used and is beginning to attract attention as a method of construction. Straightforward methods of analysis and design are available for the traditionally cast concrete member – be it a concrete floor, beam, wall or column member. This is not the case for the concrete member cast in a flexible fabric formwork.

This paper provides a state-of-the-art update on the use of fabric as a formwork for concrete construction and introduces an analytical modeling and design technique that will offer the design community, architects and engineers, 1) an alternative method for expressing themselves using flexible fabric formwork 2) the ability to optimize concrete members and 3) realize economies of construction leading to a conservation of construction materials and a *greener* more *sustainable* planet.

1 STATE-OF-THE-ART

1.1 *First formworks*

Since its invention by the Romans, concrete has been cast into all manner of formworks whether temporary or permanent. All-rigid formworks including rubble, brick and wood have become the containment form of choice for our modern concretes and an industry standard practice ever since humankind first sought to contain these early forms of mortar and "concrete" in their structures.

Historically both civil engineering and architectural projects have benefited by the use of fabric as a formwork for concrete containment. This versatile means of containing concrete saw some of its first use in civil engineering works such as erosion control. Developed and patented by Construction Techiques, Inc. in the mid-1960's Fabriform® is the original fabric-formed concrete system. Their products include Articulated Block, Filterpoint, Unimat, Concrete Bags and Pile Jackets. Engineers who have reported on the use of fabric-formed concrete lining used for slope protection include Phildysh & Wilson (1983) and Lamberton (1989).

This paper will highlight a few of those engineers, architects, designers and researchers worldwide who have made use of this unique way of forming concrete and focuses on fabric formworks for use in forming concrete members used in architectural works.

1.2 *Modern-day formworks*

One of the first architects to use a flexible formwork in an architectural application was the late Spanish architect Miguel Fisac with his 1970's design of the Juan Zurita residence in Madrid, Spain, (Fig. 1). His use of rope and plastic sheeting to create these precast panels imparts a sense of "warmth and softness".

Figure 1. Juan Zurita residence (Studio Miguel Fisac), to an otherwise cold and hard substance.

Another architect whose work has softened up concrete is Japanese architect Kenzo Unno. Working independently of Fisac he has developed several cast-in-place (CIP) fabric-formed wall systems since the mid-1990's. The Kobe earthquake on January 17, 1995 provided the motivation for Unno to create residential designs that are intended to provide safe housing

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Figure 2. Eiji Hoshino Residence (Mark West photo).

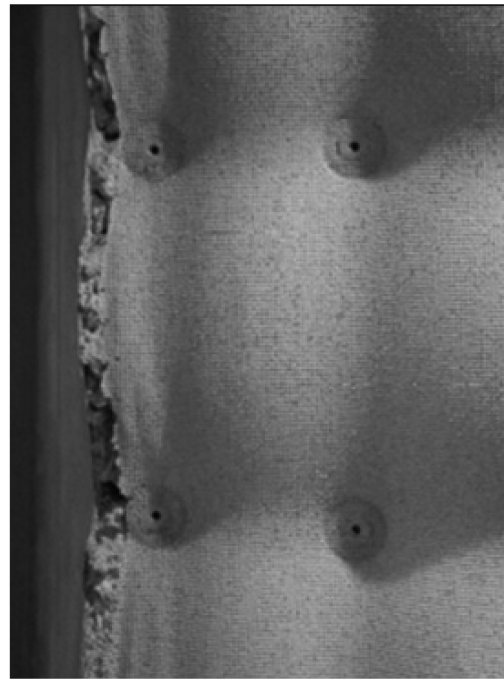

Figure 3. Quilt-like pattern detail for Eiji Hoshino Residence (Mark West photo).

using simple methods of construction with as little construction waste as possible. Using standard wall ties and the wall's reinforcement for support of the fabric membrane his quilt-point restraint method, for example, creates a pattern reminiscent of a quilt for the Eiji Hoshino Residence (Figs. 2 & 3).

For the Susae Nakashima "Stone Renaissance" house a "frame" restraint method was employed using pipes at a slight angle to restrain the fabric and give these walls their own distinct character (Fig. 4).

Two other practitioners that come to mind are Sandy Lawton, a Vermont, USA design-builder, and Byoung Soo Cho, a Seoul, South Korea architect. Lawton used geotextiles to form the columns, walls and floors for a nontraditional "treehouse" which was completed in 2007 and Cho crafted a Korean visitor center and guesthouse completed in 2009 using geotextiles to form its walls. See 'FURTHER INFORMATION' for links to these designers' websites.

Industries are sometimes slow to embrace new technologies and industries utilizing fabric formworks are few. Several industries that have benefited by using flexible formworks are; Fab-Form Industries, Ltd. based in Vancouver, British Columbia, Canada, Monolithic (air inflated domes) based in Italy, Texas, USA and Concrete Canvas Ltd. based in Pontypridd, UK.

It has been said "The beautiful rests on the foundation of the necessary. – Ralph Waldo Emerson". This quote aptly applies to fabric-formed structures as well beginning with the foundations. Since 1993 Richard Fearn, owner and founder of Fab-Form Industries, Ltd., has developed and marketed several fabric forming products including; Fastfoot® for continuous and spread footings; Fastbag® for spread footings

Figure 4. Susae Nakashima "Stone Renaissance" house (Kenzo Unno photo).

and Fast-TubeTM for piers and columns. See Fab-Form Industries' website listed under 'FURTHER INFORMATION'.

Several methods of construction using inflated forms have been available since the early 1940's but it was only recently that ACI (American Concrete Institute) Committee 334 (2005) introduced a standard guide for the construction of thin-shells using inflated forms.

David South, president and founder of Monolithic is the co-inventor of the Monolithic Dome and has been

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constructing thin-shell domes for more than 40 years. Monolithic's basic steps for constructing a dome are inflating an airform fixed to a foundation, applying a layer of polyurethane foam, hanging reinforcement and applying up to five layers of shotcrete. The inherent tensile strength of the PVC-coated or polyester fabric used for the airform allows it to be inflated to a sufficient strength to support all the applied construction materials until the concrete has cured to the point where the dome is self-supporting. Monolithic's use of fabric allowed the construction of thin-shell domes to once again be done economically. See 'Monolithics' website listed under 'FURTHER INFORMATION'.

William Crawford and Peter Brewin are directors and co-founders of Concrete Canvas Ltd., UK. Their approach to creating a concrete structure is similar to Monolithic's by using inflation to support the PVC form temporarily. However, that is where the similarity ends. The structures, which can be used as emergency shelters has a PVC form impregnated with concrete that hardens upon hydration leaving a self-supporting structure in place. The companies' concrete impregnated canvas may also be used in civil engineering projects for erosion control. See 'Concrete Canvas' website listed under 'FURTHER INFORMATION'.

1.3 *Formwork applications*

These examples highlight where flexible fabric formwork has been used forming architectural applications. Fabric forming applications include:

- Walls
- Cast-in-place
- Precast
- Shotcrete thin-shell curtain wall systems
- Beam and floor systems
- Trusses
- Columns
- Vaults
- Prefabrication of thin-shell funicular compression vaults
- Molds for stay-in-place concrete formwork pans
- Foundations
- Continuous and spread footings
- Civil engineering works
- Revetments, underwater pile jackets
- Coastal and river structures

While it is true that a flexible fabric formwork may be used nearly anywhere a rigid formwork is used, a significant amount of research remains to be done to bring these systems into everyday practical use by the construction industry. Standards and guidelines for using flexible fabric formworks need to be developed for the design community to take full advantage of this unique method of forming concrete members.

Countries with architectural and engineering students conducting most of the current research include Belgium, Canada, Chile, Denmark, England, the Netherlands, Switzerland and Scotland. The most prolific research currently being conducted is under the direction of Professor Mark West, Director of the Centre for Architectural Structures and Technology (C.A.S.T.) at the University of Manitoba, Canada.

Figure 5. Model wall panel formwork (C.A.S.T. photo).

2 BASIC PRINCIPLES

2.1 *An introduction to flexible formwork*

The author's first introduction to flexible formwork came from reading an article entitled "Fabric-formed concrete members" published in *Concrete International* by Professor West, West (2003). A visit to C.A.S.T. in June of 2004 exposed the author to this unique method of forming concrete members. Professor West and his architectural students at C.A.S.T. first began exploring the use of flexible formwork for precasting concrete wall panels in 2002, West (2002, 2004). The shape a wall panel could take was first explored using a plaster model with various interior support and perimeter boundary conditions (Fig. 5). The cloth fabric, when draped over interior supports and secured at the perimeter, deforms as gravity forms the shape of the panel with the fluid plaster as shown in the completed plaster casts (Fig. 6). Once a satisfactory design has been obtained, a full-scale cast with concrete can be made.

The casting of a full-scale panel using concrete requires finding a fabric capable of supporting the weight of the wet concrete. For this purpose, a geotextile fabric made of woven polypropylene fibers was utilized. Assorted interior supports were added to the formwork (Fig. 7) and the flexible fabric material was

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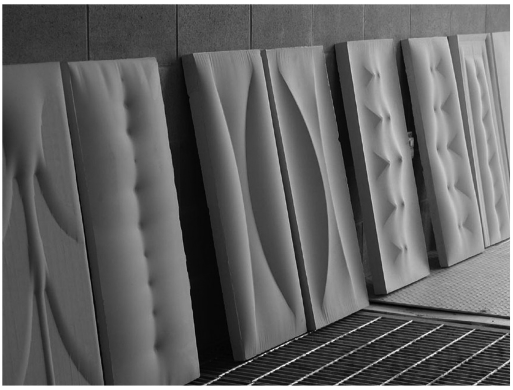

Figure 6. Completed plaster cast wall panels (C.A.S.T. photo).

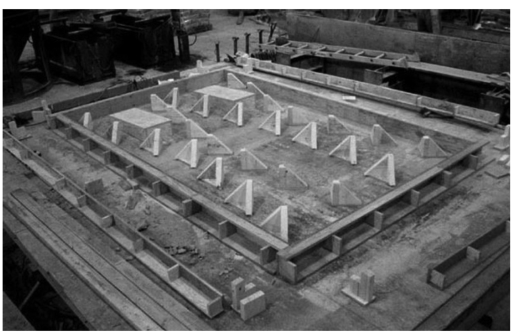

Figure 7. Placing blockouts and interior supports prior to stretching in fabric in full-scale wall panel formwork (C.A.S.T. photo).

Figure 8. Securing fabric and placing reinforcement in full-scale wall panel formwork (C.A.S.T. photo).

pretensioned at the perimeter (Fig. 8). Depending upon the configuration of these interior support conditions, three dimensional funicular tension curves are produced in the fabric as it deforms under the weight of the wet concrete (Fig. 9). The completed panel is shown in Figure 10.

Figure 9. Placing concrete in full-scale wall panel formwork (C.A.S.T. photo).

Figure 10. Completed concrete wall panels (C.A.S.T. photo).

2.2 *Supporting elements*

Geotextile fabric as a formwork has a number of distinct advantages including:

- The forming of very complex shapes is possible.
- It is strong, lightweight, inexpensive, will not propagate a tear and is reusable.
- Less concrete and reinforcing are required leading to a conservation of materials.
- Filtering action of the fabric improves the surface finish and durability of the concrete member (Fig. 3 & 11).

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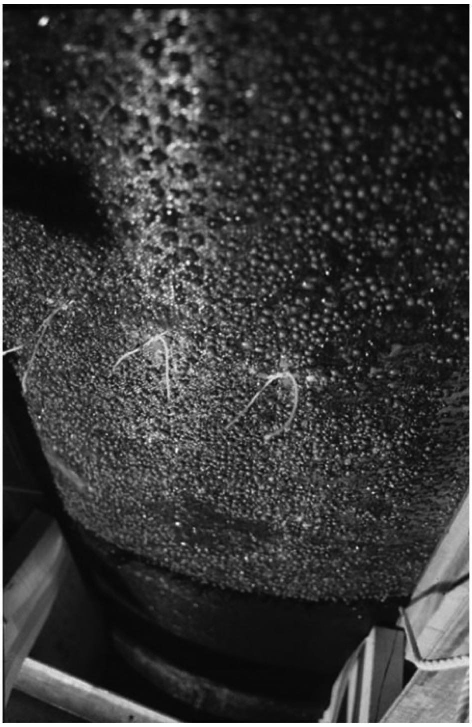

Figure 11. Filtration of excess water and air bubbles through geotextile fabric (C.A.S.T. photo).

It also has several disadvantages including:

– Relaxation can occur due to the prestress forces in the membrane.
– There is the potential for creep in the geotextile material, which can be accelerated by an increase in temperature as might occur during hydration of the concrete as it cures.
– The concrete must be placed carefully and the fabric formwork must not be jostled while the concrete is in a plastic state.

The author believes however, until new fabrics are developed the benefits of using geotextiles far outweighs any disadvantages.

3 STRUCTURAL MODELING AND ANALYSIS

3.1 *An FEA procedure for a flat cast wall panel*

The design of a fabric formed concrete panel may be approached in several ways. Each approach must take into account the panel's anchor locations to the backup framing system. One approach might be to locate the anchor points based on the most efficient panel design. Another approach could be to locate the anchor points based on the most pleasing appearance the panel takes due to the deformed fabric shape, and still another could be to consider both efficiency and appearance as a basis for the anchor locations.

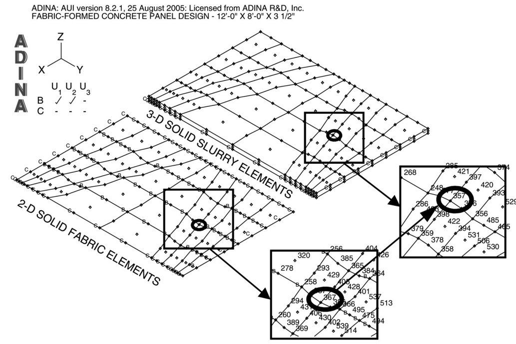

Figure 12. Form-finding concrete panel shape using finite element analysis (FEA).

How might a precast wall panel system, for example, be engineered? Straightforward methods of analysis and design are available for the traditionally cast concrete wall or floor panel. This is not so for the panel cast in a flexible fabric formwork. Shapes as complex as these require the use of finite element analysis (FEA) software. A procedure to "form-find" and analyze the complex panel shape is required (Fig. 12). Prior to a thesis and a paper by the author to introduce a design procedure that allows one to design a fabric cast concrete panel, no design procedures or methods to predict the deflected shape of a fabric cast panel had been developed, Schmitz (2004, 2006).

Briefly, the steps in this procedure are as follows:

1. Determine the paths the lateral loads take to the wall panel's anchored points.
2. Use the load paths, defined in Step 1, to model the fabric and plastic concrete material as 2-D and 3-D Solid elements, respectively. Arrangement of these elements defines the panel's lines of support.
3. "Form-find" the shape of the panel by incrementally increasing the thickness of the 3-D Solid elements until the supporting fabric formwork reaches equilibrium. The process is iterative and equivalent to achieving a flat surface in the actual concrete panel – similar to a ponding problem.
4. Analyze and design the panel for strength requirements to resist the lateral live load and self-weight dead load.

If, after a completed analysis of the panel in Step 4, it is found that the panel is either "under-strength" or too far "over-strength", adjustments to the model in Step 2 will be required and Steps 3 and 4 repeated. With this iterative process, it should be possible to obtain an optimal wall panel design. It should be noted this procedure was developed using a plain concrete model.

The structural analysis program ADINA was employed to analyze the formwork and the concrete panel cast in it. The final panel form, function and performance of the fabric membrane and the reinforcement of the panel for design loads all add to the complexities of the panel's analysis and design (Fig. 13).

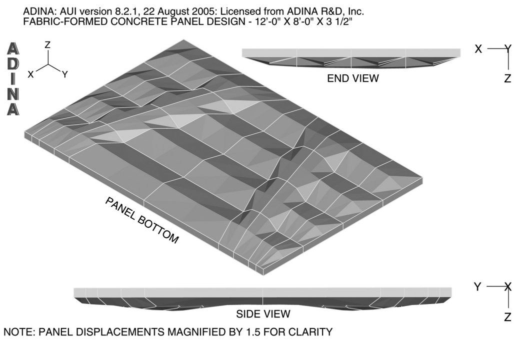

Figure 13. Final concrete panel shape using FEA.

A precast fabric-formed concrete wall panel, poured flat in a bed, may be one of the simpler concrete members to analyze, but when it comes to other concrete member shapes, one thing is clear, the system will undoubtedly be very complex and a procedure using finite element methods will be required.

3.2 *Engineering procedures for more complex forms*

Most recently, C.A.S.T. research has focused on thin-shell concrete vaults formed from fabric molds. These vaults can themselves serve as molds for stay-in-place formwork pans or glass fiber reinforced concrete (GFRC) applications. Another vault option being explored is a direct-cast fabric-formed thin-shell vault that can span between abutments in a beamlike fashion. These members are formed using a single flat rectangular sheet of fabric simply hung from a perimeter frame and used as a mold to form a double curvature vault (Fig. 14). Using a carbon fiber grid in lieu of conventional reinforcing steel allows for a creation of a very thin section – only 3 cm thick as shown in the completed vault (Fig. 15).

C.A.S.T.'s innovative work closely follows methods of funicular shell formation first pioneered by Heinz Isler. Isler used small-scale funicular models to determine full-scale geometry and structural behavior of reinforced concrete thin-shell structures.

The engineering of complex and exotic vaults and thin-shell panel shapes will require an approach different than the form-finding approach described above for a horizontal fabric formed precast panel. Whereas Isler tested small scale models of his shell structures and then scaled them up to full size these vaults and thin-shell wall panels may already be at full-scale before they are put to use. Two approaches to the engineering analysis of these thin-shell panel shapes might be considered. One is a photographic method using a commercially available software program called PhotoModeler® Scanner. This program imports images from a digital camera to create a dense point cloud and mesh data, which can be exported to FEA software. Another method might be to use High Definition Laser Scanning which also creates a dense point cloud and mesh data which can be exported to FEA software.

Figure 14. Fabric mold stretched lengthwise in frame to form double curvature funicular thin-shell vault (C.A.S.T. photo).

Figure 15. Completed double curvature funicular thin-shell vault (C.A.S.T. photo).

Both approaches will involve an iterative process where one would first image the basic member shape and then analyze it for the superimposed design loads. Results of the first analysis would show where weak points in the member occur. Further analysis would suggest to what degree the member needs to be built-up using additional textile reinforcement and concrete materials.

4 CONCLUSIONS AND FURTHER RESEARCH

4.1 *Conclusions*

By utilizing a flexible fabric formwork, such as a geotextile, several advantages have been noted:

– The forming of very complex shapes is possible.

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- Improved surface finish and durability – due to its filtering action.
- A more efficient and sustainable design is possible since material is placed only where it is needed – "form follows function".
- Flexible fabric formwork increases freedom of design expression and can spark the imagination of architects and designers to think beyond the simple prismatic shape.
- The development of a fabric formwork system has the potential to significantly reduce man's impact on the environment in terms of materials and energy usage.

4.2 *Further research needs*

The advancement of *Fabric-formed Concrete* would be furthered by:

- Design and modeling verification for research work being done on precast concrete wall panels.
- Investigating reinforcement options:
  - Fiberglass rebar
  - Alkali resistant (AR) glass textile
  - Carbon-fiber grids
- Finding the most advantageous reinforcing textiles for the reinforcement of all fabric-formed members including thin-shell shapes.
- The development of new fabrics, with improved properties over those of geotextile fabrics, for use as flexible formworks.
- The development of standards and guidelines for use in precast and cast-in-place forming systems are needed for this method of forming to be of practical use to the design community.

5 FURTHER INFORMATION

Readers interested in additional information are encouraged to visit the following websites especially, the C.A.S.T. website at the University of Manitoba where numerous examples and literature on this topic may be found.

- Author's research dedicated website: http://www.fabwiki.fabric-formedconcrete.com/
- The Centre for Architectural Structures and Technology (C.A.S.T.) at the University of Manitoba, Canada: http://www.umanitoba.ca/cast_building/
- The International Society of Fabric Forming (ISOFF): http://www.fabricforming.org/
- Byoung Soo Cho Architects, South Korea: http://www.bchoarchitecs.com/
- Sandy Lawton ARRODESIGN, Vermont, USA: http://www.arrodesign.org/
- Fab-Form Industries, Ltd., BC, Canada: http://www.fab- form.com/
- Monolithic (air inflated domes), Texas, USA: http://www.monolithic.com/
- Concrete Canvas Ltd., Pontypridd, UK: http://www.concretecanvas.co.uk/

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