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Fabric-formed Concrete Structures, a Unique Way of Forming Concrete

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ABSTRACT

Since its invention by the Romans, concrete has been cast into all manner of formworks whether temporary or permanent. Concrete members have traditionally been cast using a rigid formwork and engineering analysis has been on prismatic members. 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. But, since the 1970's there has been a renewed interest in using modern fabrics as part of concrete member forming systems. This type of forming system is not easily engineered and its analysis is very complex and requires nonlinear analytical procedures. Could this be a hindrance to its everyday use and acceptance? This paper explores the question of whether there is a future for the use of fabric as a material practical for forming concrete members.

INTRODUCTION

A brief look at the history of using fabrics for casting concrete – a timeline

Before we look to the future, we shall briefly look to the past. A paper by D. Veenendaal et al. (2011) gives a detailed accounting of innovators who have gone before us using fabric as part of their building forming systems, as hydraulic and geotechnical structures, as form liners and as the membrane in their pneumatic formed structures. We shall define fabric formwork as a flexible membrane for the support of fluid concrete used to form structural members. A chronology of 20th century innovators and their contributions to building systems is given in Table 1.

Table 1. A chronology of 20th century innovators and their contributions to building systems

Date	Innovator	Contribution
1899	Gustav Lilienthal	patents a suspended ceiling system using an impermeable fabric capable of supporting a concrete floor
1934	James H. de W. Waller	patents a fabric-formed system using hessian fabric for numerous building components
1937	Dennis Farrar et al.	patents a fabric-formed suspended floor/roof system using hessian fabric
1941	Wallace Neff	patents a pneumatic forming system suggesting the use of a rubber-impregnated canvas for forming thin-shell barrels and domes
1947	Kurt Billig	patents a roof forming system using in part a hessian fabric
1948	K. Billig, J. Waller	builds corrugated concrete shell roof structures utilizing hessian fabric

Table 1 cont.

1949	Felix Candela	utilizes burlap sacks over wooden arches to form a corrugated shell roof
1970	Miguel Fisac	utilizes restrained polyethylene sheeting to form facades
1971	Sidney Parker	patents a suspended floor/ceiling system using steel bands and flexible sheeting
1992	Mark West	builds experimental full-scale fabric-formed slab with integral beams and columns using woven geotextiles (West 2001)
1993	Richard Fearn	patents the first of several flexible formwork systems for use in foundations
1995	Mark West	patents a method of forming a concrete column capital using a flexible tension membrane material (West 1995)
1997	Kenzo Unno	utilizes scaffold netting as a formwork membrane and part of a reinforced concrete wall formwork system

Not to be forgotten are those innovators mentioned in this historical perspective by the Veenendaal et al. paper that contributed to or influenced the work of those listed above. Most influential were those innovators who used woven geotextiles for their civil engineering works such as revetments, underwater pile jackets, pond liners and coastal and river structures. Their research found that geotextiles offered superior concrete finish and durability, had exceptional strength and were a very economical way for containing concrete (Lamberton 1989). Applications where fabrics, used as form liners, were also shown to improve the surface quality and finish of the cast concrete member.

Innovation – finding form

Concrete being such a fluid and dynamic material is in search of its identity. It finds that identity once it has been contained. 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. A few of the architects and engineers who used the forming materials at hand to create expressive forms out of concrete and masonry are listed below (Tang 2012).

- Antoni Gaudi (1852-1926)
- Robert Maillart (1872-1940)
- Pier Luigi Nervi (1891-1979)
- Felix Candela (1910-1977)
- Eladio Dieste (1917-2000)
- Heinz Isler (1926-2009)
- Miguel Fisac (1913-2006)

Many of these early innovators pushed the computational analysis envelope available at the time. Some, like Antoni Gaudi, looked to nature for inspiration. The question we might ask ourselves is: Do we need to "reinvent forming" or just draw from nature, i.e. gravity – catenary action?" as Gaudi did. Gravity as a tool vs. a force to be reckoned with and controlled in conventional formwork. Alan Chandler in *fabric formwork* (Chandler 2007) notes "…for Felix Candela and Christopher Alexander fabric acted as a permanent shutter (formwork)…". Chandler speaks of the family of fabric construction that includes:

- Tensile structures
- Pneumatic structures
- Hydrostatic structures and
- Shell structures derived from membrane form-finding

When faced with extremely complicated and complex shapes Heinz Isler and Antoni Gaudi used fabric as a modeling tool (Chilton 2012, Bechthold 2008, Billington 1983). These visionaries recognized that hanging chains and fabrics, forming catenaries, are in pure tension and when inverted are in pure compression and very stable. Gaudi, whose Catalan vaulting preceded the works of Candela preferred funicular polygon shapes and catenaries to straight lines and looked to nature and natural forms – an approach today called biomimicry – a new science that studies nature's models (Cirlot 2011, Pronk et al. 2008). Gaudi, as a modernist architect, married natural forms with modern materials and one only wonders what he would have created had today's modern synthetic fabrics been available to work with.

Formwork applications

From this family of fabric construction, listed above, what potentially practical applications exist? Fabric forming applications include:

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

And, 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 and feel comfortable using it. So what is the current state-of-the-art? Following are several architectural examples.

STATE-OF-THE-ART

Architectural 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, Figure 1. His use of rope and plastic sheeting to create these precast panels imparts a sense of "warmth and softness" to an otherwise cold and hard substance. Fisac used this method throughout the 1970's to form the cladding of a number of structures (Veenendaal 2011).

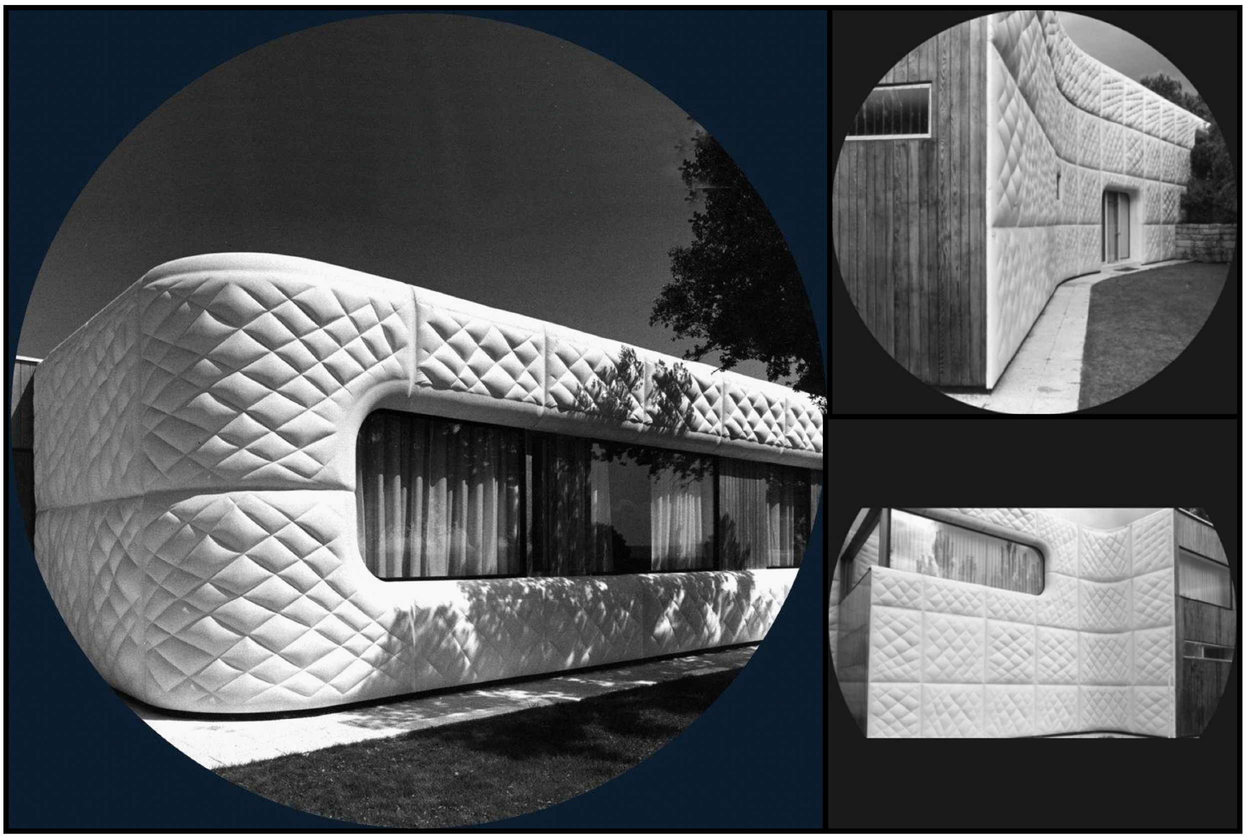

Figure 1. Juan Zurita residence (Studio Miguel Fisac).

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 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, Figure 2.

Several other practitioners that come to mind are Sandy Lawton, a Vermont, USA design-builder, Geoff Morrow, a structural engineer with StructureMode, London, UK based engineering firm 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, Cho crafted a Korean visitor center and guesthouse completed in 2009 using geotextiles to form tilt-up panels for its walls and Morrow used fabric formwork cast the concrete frame in 2015 for a new school and community center in Cambodia.

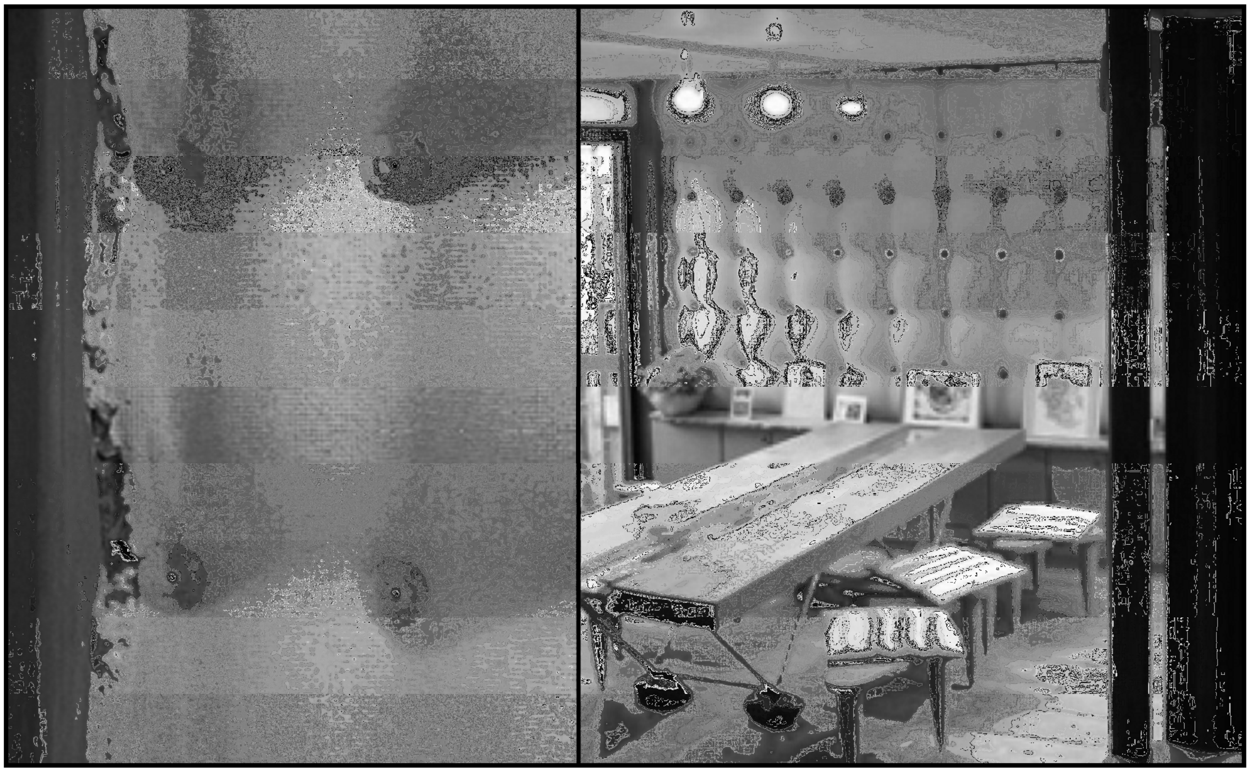

Figure 2. Quilt-like formwork pattern used for the Eiji Hoshino Residence (Mark West photos).

Foundation formworks

Industries are sometimes slow to embrace a new technology like fabric formworks but several that have benefited 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 and Fast-Tube™ for piers and columns.

Pneumatically formed structures

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 introduced a standard guide for the construction of thin-shells using inflated forms (ACI Committee 334 2005). David South, president and founder of Monolithic is the co-inventor of the Monolithic Dome and has been 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.

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 have 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.

RESEARCH EFFORTS

Fabric forming rebirth

The person most responsible for "spreading the word" on the benefits of fabric-formed concrete is Mark West, an architect, educator and artist. Mark West first began experimenting with flexible formworks in 1986 and had a vision for the creation of a center and research facility where architectural and engineering students and researchers could experiment with and explore this unique way of forming concrete. That vision was fulfilled with the creation of The Center for Architectural Structures and Technology (C.A.S.T.) on the campus of the University of Manitoba, Winnipeg, Canada in 2001.

Several articles written by Professor West and published in *Concrete International* were the author's first introduction to flexible formwork (West 2003, West 2004). For more than two decades, Professor West and his architectural students at C.A.S.T. have been exploring the use of flexible formwork for casting concrete wall panels and other structural members.

The shape a wall panel could take was first explored using a plaster model with various interior and perimeter boundary conditions. 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 Figure 3. 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 by C.A.S.T. The flexible fabric material was pre-tensioned in the formwork and assorted interior supports were added. Depending upon the configuration of these interior support conditions, three-dimensional funicular tension curves were produced in the fabric as it deformed under the weight of the wet concrete. Figure 4 shows the rigid frame and internal supports prior to stretching in the geotextile fabric and the completed concrete wall panel.

The potential benefits for using a flexible fabric formwork include increased freedom of design expression, a design where "form follows function", economies of construction, and improvement in the finish and durability of the product. Moreover, while a building project may require a wall panel for purely functional reasons, such as resisting the required lateral loads and keeping the weather out, aesthetic reasons may require these panels to be expressive in the form they take. From an engineering perspective, however, the challenge remains of finding a method to analyze the complex structural shape a wall panel could ultimately take.

Figure 3. Model formwork and completed plaster cast (C.A.S.T. photos).

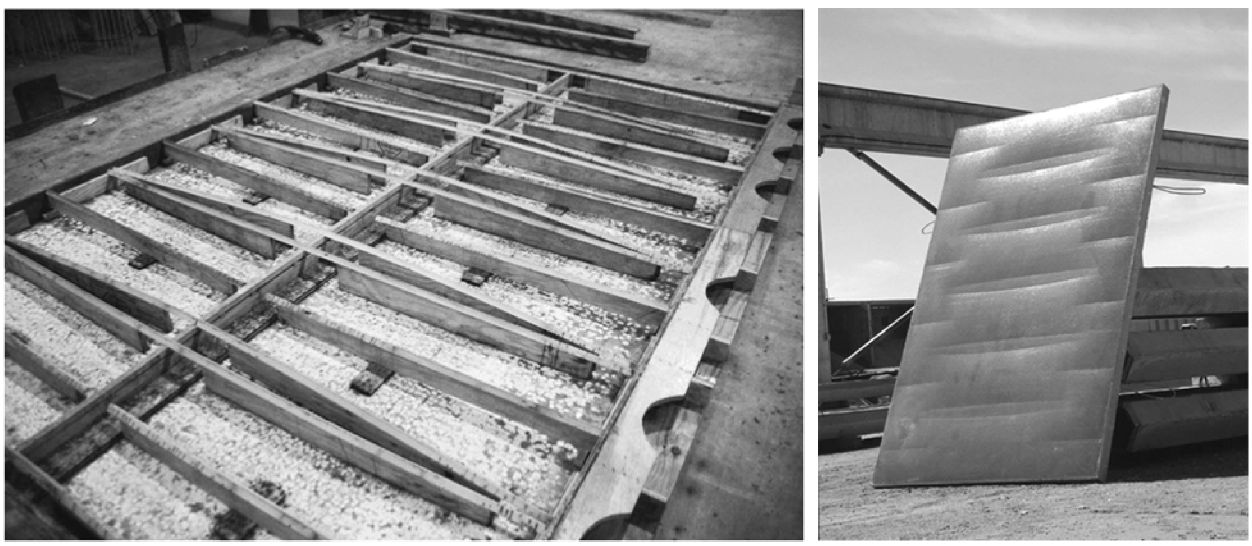

Figure 4. Full-scale formwork and completed concrete wall panel (C.A.S.T. photos).

International contributions

The list of countries with universities and research centers researching fabric-formed concrete continues to grow including: Austria, Belgium, Canada, Chile, China, Denmark, England, Germany, India, Ireland, Japan, Libya, Northern Ireland, Poland, Scotland, Sweden, Switzerland, the Netherlands and the United States.

To date three fabric-formed concrete conferences have been held; 2008 – at C.A.S.T., 2012 – at the University of Bath, UK and 2015 – at Het Muziekgebouw (The Music Building) Amsterdam, the Netherlands. Out of these dedicated conferences have come more than 75 papers and presentations on this topic. In addition, since that first conference numerous other workshops and invited conference sessions have been held where likeminded researchers have gathered to share their work and explore new options. Therefore, it would appear, from at least the international scene the movement, if it can be called that, is alive and well. If there continues to be an interest in researching this topic and researchers can cultivate that interest with the design community it is quite possible we may see more fabric-formed concrete members and structures in the future.

HURDLES

Innovation – disruptive technologies

Case-in-point, wooden (rigid) forms have been a hindrance to fully exploiting the properties and potential of concrete and University of Edinburgh Professor Remo Pedreschi described fabric formwork as a "disruptive technology" (Pedreschi 2012). What is meant by this?

The term, disruptive technologies, was coined by Clayton M. Christensen and introduced in a 1995 article, which he cowrote with Joseph Bower. He further describes the term in his book *The Innovator's Dilemma: when new technologies cause great firms to fail* in which he describes the types of innovation as sustaining or disruptive. For example, take what he has to say about the electric vehicle.

"….., as an automotive company executive, I would worry about the electric vehicle, not just because it is politically correct to be investing in environmentally friendly technologies, but because electric vehicles have the smell of a disruptive technology. They can't be used in mainstream markets; they offer a set of attributes that is orthogonal to those that command attention in the gasoline-powered value network; and the technology is moving ahead at a faster rate than the market's trajectory of need.

Because electric vehicles are not sustaining innovations, however, mainstream automakers naturally doubt that there is a market for them—another symptom of a disruptive innovation." (Christensen 1997).

A sustaining technology is one that does not affect existing markets and a disruptive technology is one that creates a new market by applying a different set of values. Will the electric vehicles overtake the existing gasoline driven market? Hybrid vehicles, introduced to bridge the gap, have garnered less than 2% of the total vehicle market share from 1999-2014 (Wikipedia 2015). While electric vehicles are making inroads they have yet to take over and only time will tell whether they will make a significant impact on the motoring public.

After reviewing recent e-mail correspondence from three of the leading proponents of fabric formwork, Richard Fearn of Fab-Form Industries and Professors Remo Pedreschi and Mark West I get the impression that making an immediate and significant industry impact is indeed difficult. All three indicate that the very nature of the marketplace is complex and that for the builder, who may be selected solely based on his/her low bid, he/she may be reluctant to take on an unknown system. There is a risk involved when pursuing new means of construction (R. Pedreschi, M. West, R. Fearn, personal communication, March 10, 2015). However, Professor Pedreschi says we should not see fabric formwork as a replacement but a new "disruptive technology" that offers us the opportunity to design formwork in a new way.

Acceptance of innovative technologies

There are a number of issues and hurdles to be overcome before architects, engineers and especially concrete contractors are accepting of this unique method of forming concrete. Geotextile fabric as a formwork has a number of distinct advantages including:

- The formation of very complex shapes is possible.

- It is strong, lightweight, inexpensive, reusable and will not propagate a tear.
- Less concrete and reinforcing are required resulting in a conservation of materials.
- Filtering action of the fabric improves the surface finish and member durability (Lamberton 1989, Abdelgarder and El-Baden 2012, Delijani 2010).

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 not jostled while the concrete is in a plastic state.

Finding fabric with ideal structural properties will be a challenge but, in a laboratory on the campus of MIT, Professor Yoel Fink head of the Advanced Functional Fabrics of America (AFFOA) consortium and colleagues are developing new “smart” fabrics, (Keats 2018). These new materials, which have electronics woven into them, make them functional. You might, for example, wear them to generate electricity or read your vital signs. Structurally, using the piezoelectric effect a mesh woven into a flexible formwork might work in a “feedback” mode giving you performance information, stress, strain and deflections. However, until new fabrics are developed, the benefits of using geotextiles far outweigh any disadvantages.

Additionally, to be of practical use to the design community, some standardization of systems and guidance are needed for contractors to feel comfortable using flexible formworks. Otherwise this method of forming concrete will remain a niche market exploited only by those brave and bold enough to challenge the status quo.

ENGINEERING COMPLEX FORMS

The author and several others have explored the analysis of these complex forms (Bhooshan and Sayed 2012, Veenendaal and Block 2012, Veenendaal 2008). My research involved the development of an FEM (finite element method) procedure to design a fabric cast wall panel (Schmitz 2004, 2006). Concrete wall panels have traditionally been cast using conventional prismatic formwork. Straightforward methods of analysis and design are available for the traditionally cast concrete wall or floor panel. This is not so for the wall panel cast in a flexible fabric formwork. As detailed in our 2006 paper the results show that structural value may be gained from the unreinforced concrete alone just by its positioning in the formwork. Following is a brief description of the procedure and key results.

A 4-step procedure

This procedure invokes nature, i.e. gravity, as the prime form-finding mechanism. The fabric, as a flexible membrane, is the containment device for the fluid concrete. For the structural member, a wall panel under review, it means the flexible formwork is constrained only at its perimeter and is free to deflect as gravity dictates between any interior supports used to add aesthetic definition and purpose to it. The membrane itself may or may not be prestressed. The four steps of this procedure are:

1. Determine the paths the lateral loads take to the wall panel’s anchor 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 final 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.

By utilizing the above four-step procedure, it is expected that obtaining an optimal panel shape is possible. The procedure becomes an iterative process. If, after an analysis of the panel is made 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.

Form-finding results

Figure 5 shows the process of form-finding and results of Step 3 above. It is important to note that the form-finding process requires a concrete material model that at this point does not contribute strength to the combined model. Therefore, we used a material model representing the concrete with little if any strength termed the "slurry" material model.

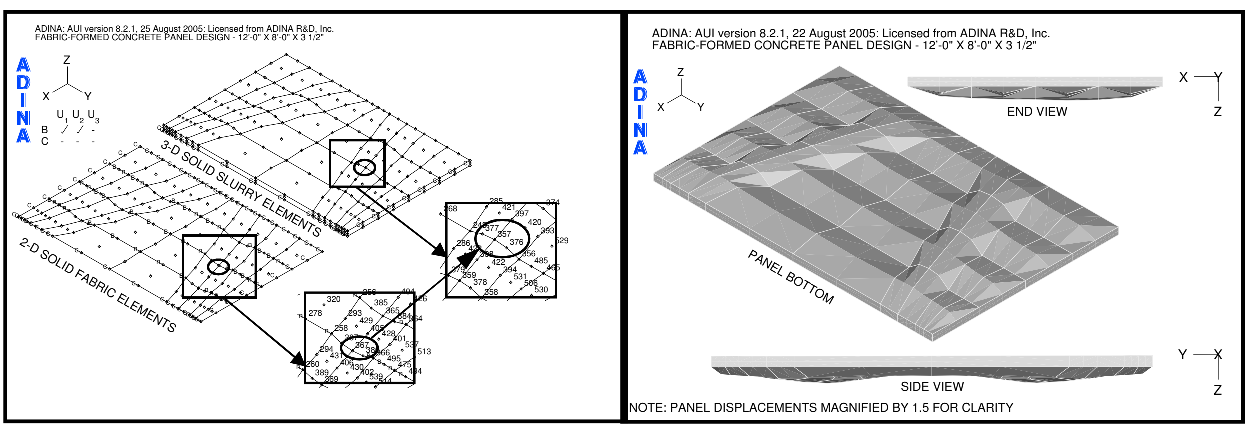

Figure 5. "Form-finding" combined fabric and slurry model (left), resultant panel shape (right) (Figures by RPS).

Analysis results

Figure 6 shows the results after the analysis of Step 4 is complete. The fabric element model has been removed, the slurry material model has been replaced with a plain concrete material model, the new boundary conditions have been imposed and the appropriate lateral and self-weight loads applied.

These resulting principal stresses are at the factored positive and negative lateral loads. We observed that the back of the panel has significantly less stress under positive lateral load than that of the front under a negatively applied lateral load. We can attribute this strength increase, under the positive load case, to arching action between supports – the direct result of the three-dimensional funicular tension curves produced in the fabric as it deformed under the weight of the wet concrete.

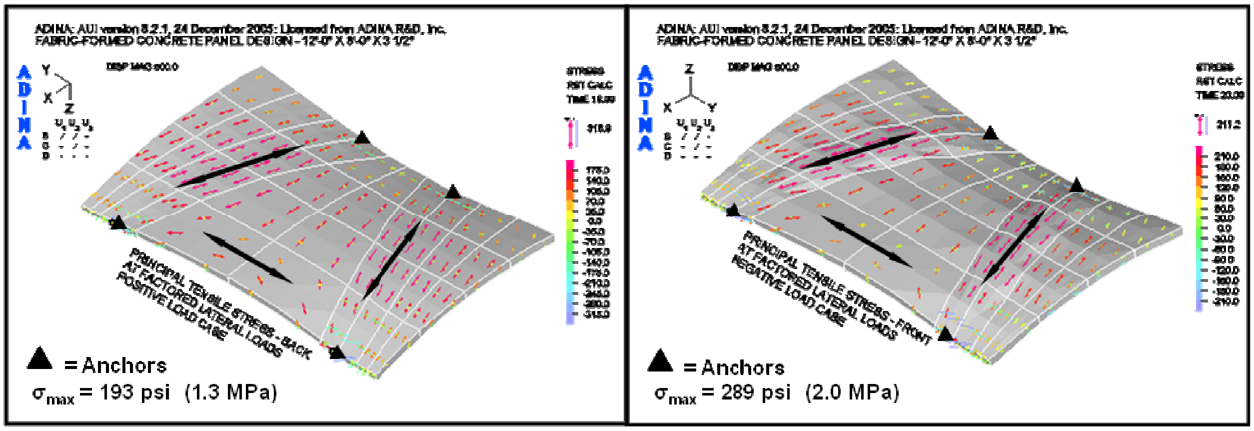

Figure 6. Panel principal stresses, back (left) and front (right) (Figures by RPS).

Figure 7 shows the effect of arching action similar to a strut and tie model under the positive lateral loads. Compressive forces in these curved panel elements, created under the positive lateral load, allow the panel loads to be steadily increased without the interior of the panel cracking.

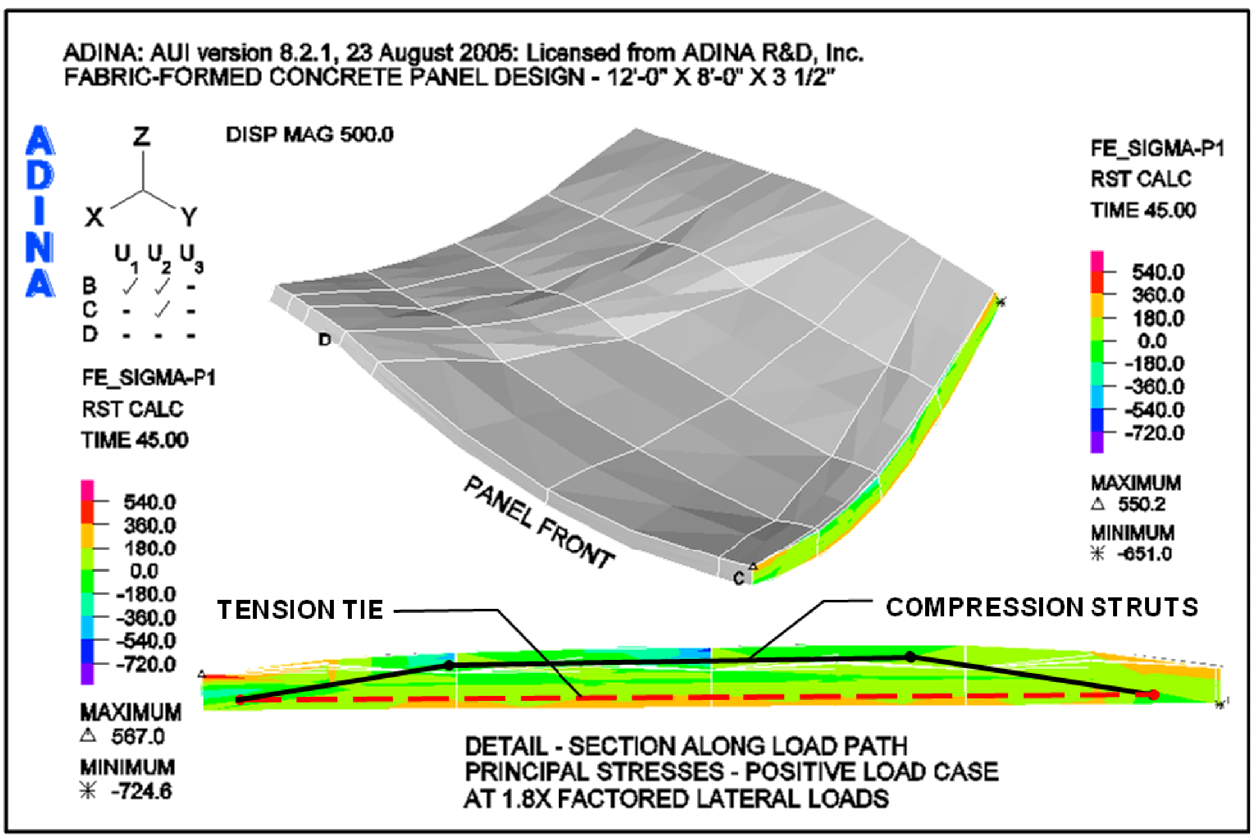

Figure 7. Panel principal stresses under positive loads along diagonal rib (Figures by RPS).

FINDING PRACTICAL SYSTEMS

We see from the structural analysis above that there are some serious benefits resulting from the flexible forming used. We know that in the "real world" some measure of reinforcing would be required but we would like that reinforcing to be non-metallic and limited to what is absolutely necessary. A conservation of materials is one of our goals.

A concept model

Like the students at C.A.S.T. we employed the creation of a plaster model to view a physical three dimensional model. Figure 8 shows the formwork used to create the plaster model. Figure 8a shows the rigid frame and intermediate supports. Figure 8b shows the fabric stretched and secured over the frame. Figure 9 shows the resulting fabric-cast plaster model.

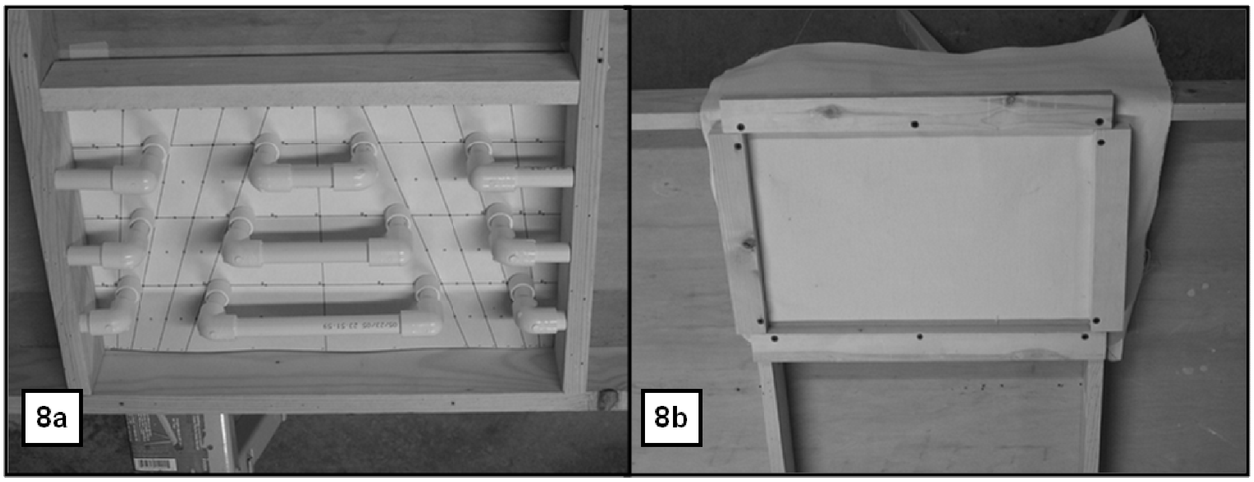

Figure 8. Plaster model formwork rig (RPS photos).

Figure 9. Fabric-cast plaster model (RPS photo).

From concept model to concept wall system

The thought occurs that if two of these panels were sandwiched together a great deal of strength could be gained from both panels acting together. The outside panel, through funicular action, would take the majority of the positive lateral load action and the inside panel would take the majority of the negative load action. Figure 10 shows what such a precast panel might look like. Figure 10a shows an elevation of the wall panel and Figure 10b a section through it. Figure 10c shows the assemblage of two panels over a layer of rigid insulation.

Those diagonals and horizontal 'ribs" are like the "bones" of your body, the spine taking the vertical loads and horizontal loads from your ribs. So, while not shown here, one could imagine this wall panel being a component in a building system where beams framing a floor system could be supported on these diagonals. Your imagination is your only limitation.

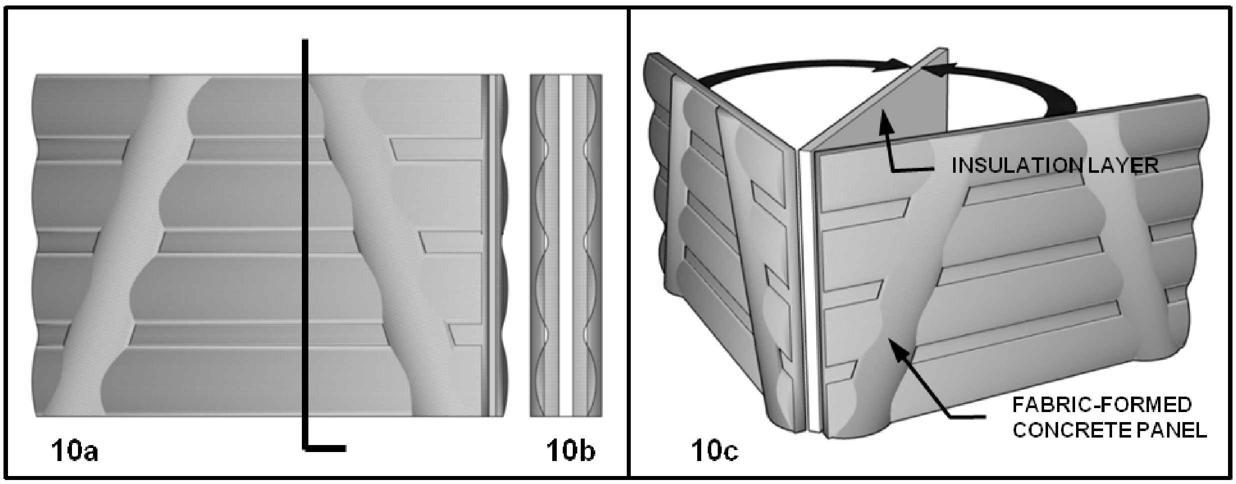

Figure 10. Computer aided design drawing of a fabric-cast wall panel system (Figures by RPS).

Fabric-formed façade systems

Two architects from Playa Vista, California, Joseph Sarafian and Ron Culver, having formed the company Form Found Design and have taken fabric formwork to a new level by using robotics to precisely position the fabric formwork. Their robotically controlled system allows for the "…flexible fabric formwork [to become] the means of rapid, replicable and economic production where geometrically complex concrete objects can be accurately fabricated with practically infinite organic variation and texture." (Sarafian and Culver 2016).

CONCLUSIONS

This paper explored the past, present and future of fabric-formed concrete structures posing the question: "Is there a future for fabric-formed concrete structures?" with the question focusing on directly cast structural members (Schmitz 2016). Given the current level of research and enthusiasm expressed at the most recent conference, we believe the answer is ***maybe***.

The list of universities conducting research and experimenting with fabric formwork continues to grow but currently a disconnect exists between the research being conducted and industry. Practitioners: architects, engineers and contractors have yet to embrace this forming method as a replacement for or an addition to their conventional formwork systems. We realize that wood and/or metal used for forming will not be totally eliminated but can be reduced to essential components thereby saving natural resources. From a practical point of view, the answer may be one where fabric formworks do not replace but supplement conventional forming methods.

If universities continue to experiment and research this forming method, it will live on, eventually gain support and make a difference in the way we construct the built environment.

This fabric forming concrete method has properties, structural advantages unique to its use as outlined above, and we fully expect to see it grow beyond the "niche" or novelty forming method marketplace it currently occupies. It will just take collaboration with industry and time.

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