Is there a future for fabric-formed concrete structures?

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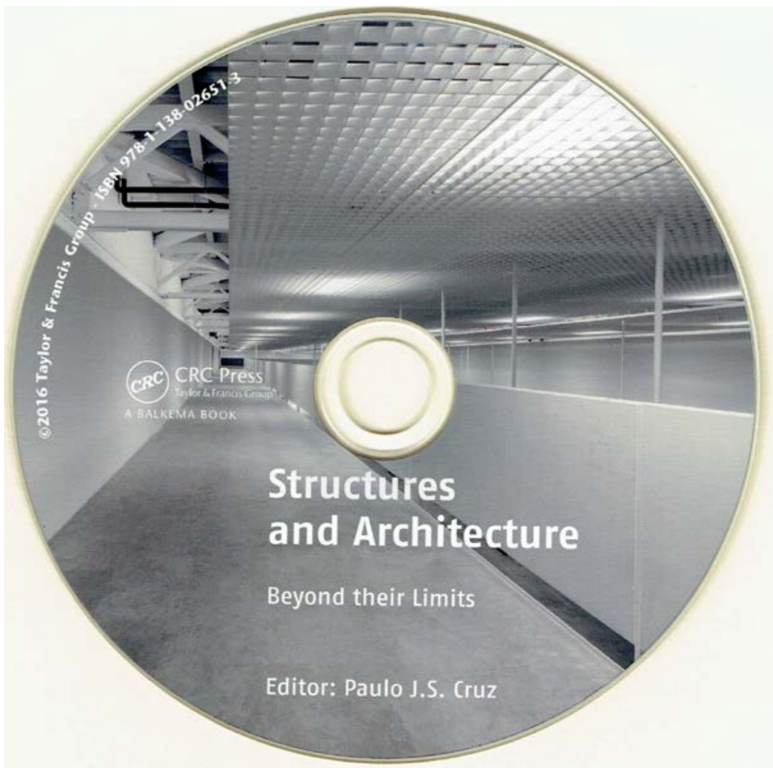

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ABSTRACT: Since its invention by the Romans, concrete has been cast into all manner of formworks whether temporary or permanent and these formworks have all been rigid. While historically both civil engineering and some state-of-the-art architectural projects have benefited by the use of fabric as a formwork this versatile means of containing concrete has yet to become a formwork of choice for the construction industry. The list of universities conducting research and experimenting with fabric formwork continues to grow but currently there exists a disconnect 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. This paper will explore the question of whether there is a future for the use of fabric as a material practical for forming concrete members.

1 INTRODUCTION

1.1 *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 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. Therefore, in light of our paper title we shall define fabric formwork as a flexible membrane for the support of fluid concrete used to form structural members. Table 1 gives a chronology of 20th century innovators and their contribution to building systems.

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

Date	Innovator	Contribution
1899	Gustav Lilienthal	patents a suspended ceiling system using an impermeable fabric capable 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	build corrugated concrete shell roof structures utilizing hessian fabric
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

Table 1 cont.

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 an RC 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). Additionally were those applications where fabrics, used as form liners, were also shown to improve the surface quality and finish of the cast concrete member.

1.2 *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. 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. As a student in his first concrete course, I favored this material as I felt I could form and build anything due to its fluid and versatile nature and I too learned to design concrete members using conventional formwork. Flexible membranes were not even part of the design equation. 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 he had today's modern synthetic fabrics to work with.

1.3 *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

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.

It should also be recognized that wood and/or metal used for forming is not totally eliminated by using fabric but can be reduced to essential components thereby saving natural resources.

1.4 *Innovation – disruptive technologies*

Case-in-point, wooden (rigid) forms have been a hindrance to fully exploit 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 (Pedreschi 2015, West 2015, Fearn 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. So what is the current state-of-the-art? Following are two architectural examples.

2 STATE-OF-THE-ART

2.1 *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).

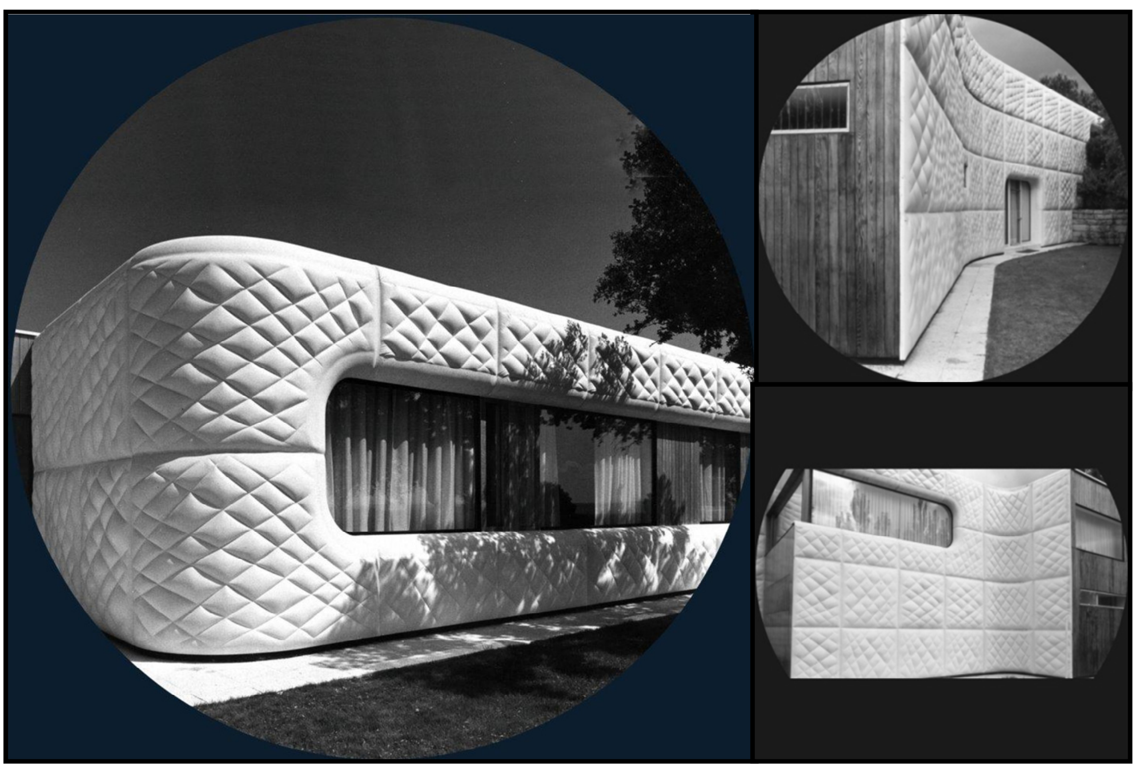

Figure 1. Juan Zurita residence (Studio Miguel Fisac).

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. See Umi Architectural Atelier website listed under 'FURTHER INFORMATION'.

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

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 tilt-up panels for its walls. See 'FURTHER INFORMATION' for links to these designers' websites.

2.2 *Foundations*

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

2.3 *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. See Monolithic's 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 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. See Concrete Canvas' website listed under 'FURTHER INFORMATION'.

3 RESEARCH EFFORTS

3.1 *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. Professor West 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.

As a result of my exposure to this forming system I used it as the subject of a Capstone Project when pursuing a Master's in Structural Engineering (Schmitz 2004). The Capstone Project was of a basic structural form, a precast wall panel, yet the analysis was complex. Implementing practical methods of analysis using off-the-shelf software is one of many hurdles this forming system must overcome before becoming a mainstream forming system.

3.1.1 *The rebirth suffers a setback*

After devoting so much effort to establishing C.A.S.T. it was unfortunate to learn that C.A.S.T. and its website were shuttered and Professor West no longer at the university. Many documents and research papers are at present unavailable and it is hoped he will reestablish a website devoted to his research. In the meantime, it will be up to those researchers in the international community to carry on and promote the work for which he has been an inspiration.

3.2 *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.

4 HURDLES

4.1 *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 & 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.

However, until new fabrics are developed the benefits of using geotextiles far outweighs any disadvantages. In addition, unless standards and guidelines for use in precast and cast-in-place forming systems are developed this method of forming concrete will remain a niche market exploited only by those brave and bold enough to challenge the status quo. ACI Committee 347 has addressed rigid formwork since 1963 but it was only recently (2005) that ACI Committee 334 introduced the construction of shells using inflated forms even though several methods of construction using inflated forms have been available since the early 1940's (ACI Committee 334 2005, ACI Committee 347 2014). 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.

At a recent ACI chapter meeting, I presented on this topic and held a question and answer period at the end. I posed the question "Is there a future for ____?" where the blank was several of the formwork applications noted above. Each question was met with silence. Many of the attendees work for the concrete industry in construction. At present, it seems, at least locally, this forming system is more of a curiosity than a breakthrough forming technology.

4.2 *Engineering complex forms*

The author and several others have explored the analysis of these complex forms (Bhooshan & Sayed 2012, Veenendaal & 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. Following is a brief description of the procedure and key results detailed in our paper (Schmitz 2006).

4.2.1 *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 implication is that the above 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.

4.2.2 *Form-finding results*

Figure 3 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.

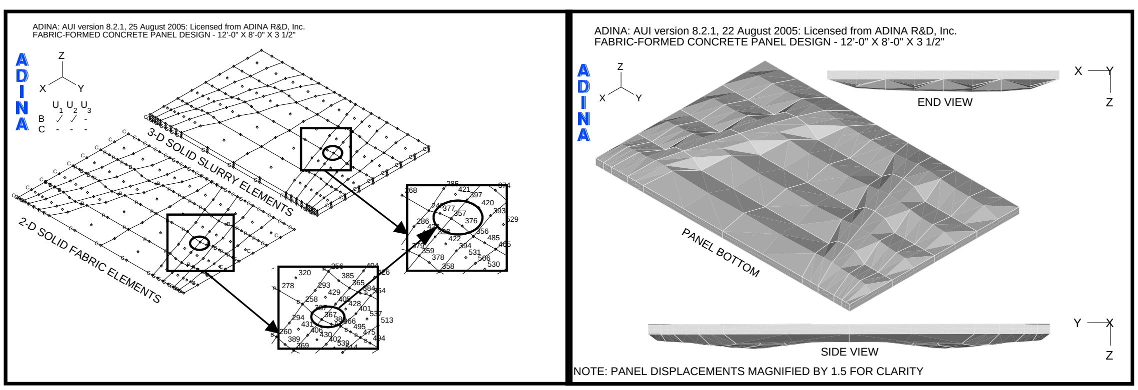

Figure 3. "Form-finding" combined fabric and slurry model (left), resultant panel shape (right).

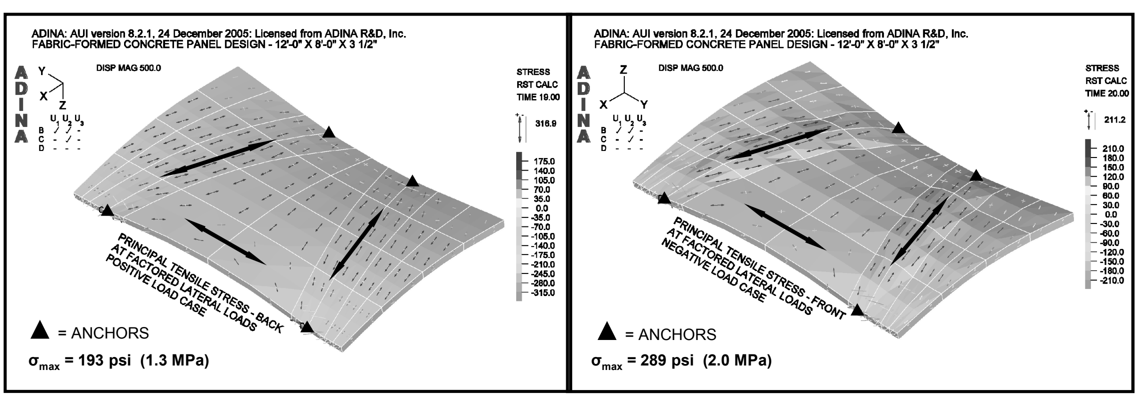

Figure 4. Panel principal stresses, back (left) and front (right).

4.2.3 *Analysis results*

Figure 4 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 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 back 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.

5 CONCLUSIONS

5.1 *IASS/ISOFF 2015 – FUTURE VISIONS*

Recently, The International Association of Shell and Spatial Structures (IASS) and The International Society of Fabric Forming (ISOFF) held joint symposia in Amsterdam, the Netherlands. Each organization had their own tracks including presentations and workshops. The ISOFF paper track highlighted current research using fabric forming for some of the applications noted above. The paper track and workshop also introduced new forming methods, such as vacuumatics, double curved surfaces using mesh and actuators, etc.

The initial methods introduced by Mark West and his students at C.A.S.T. are still popular but, like Disney's Imagineers, new forming methods continue to be introduced as researchers explore and expand the ways flexible membranes may be used.

5.2 *Is there a future for fabric-formed concrete structures?*

This paper posed the question: "Is there a future for fabric-formed concrete structures?" with the question focusing on directly cast structural members. Given the current level of research and enthusiasm, that was expressed at the most recent conference; we believe the answer is ***maybe***.

As noted previously a disconnect currently exists between academia 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. 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 in Section 4.1, 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.

6 FURTHER INFORMATION AND REFERENCES

Readers interested in additional information are encouraged to visit the following websites:

- Author's research dedicated website: http://www.fabwiki.fabric-formedconcrete.com/
- The International Society of Fabric Forming (ISOFF): http://www.fabricforming.org/
- Umi Architectural Atelier: http://www.umi-aa.com/architecture-en/
- 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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