Fabric forms for architectural concrete

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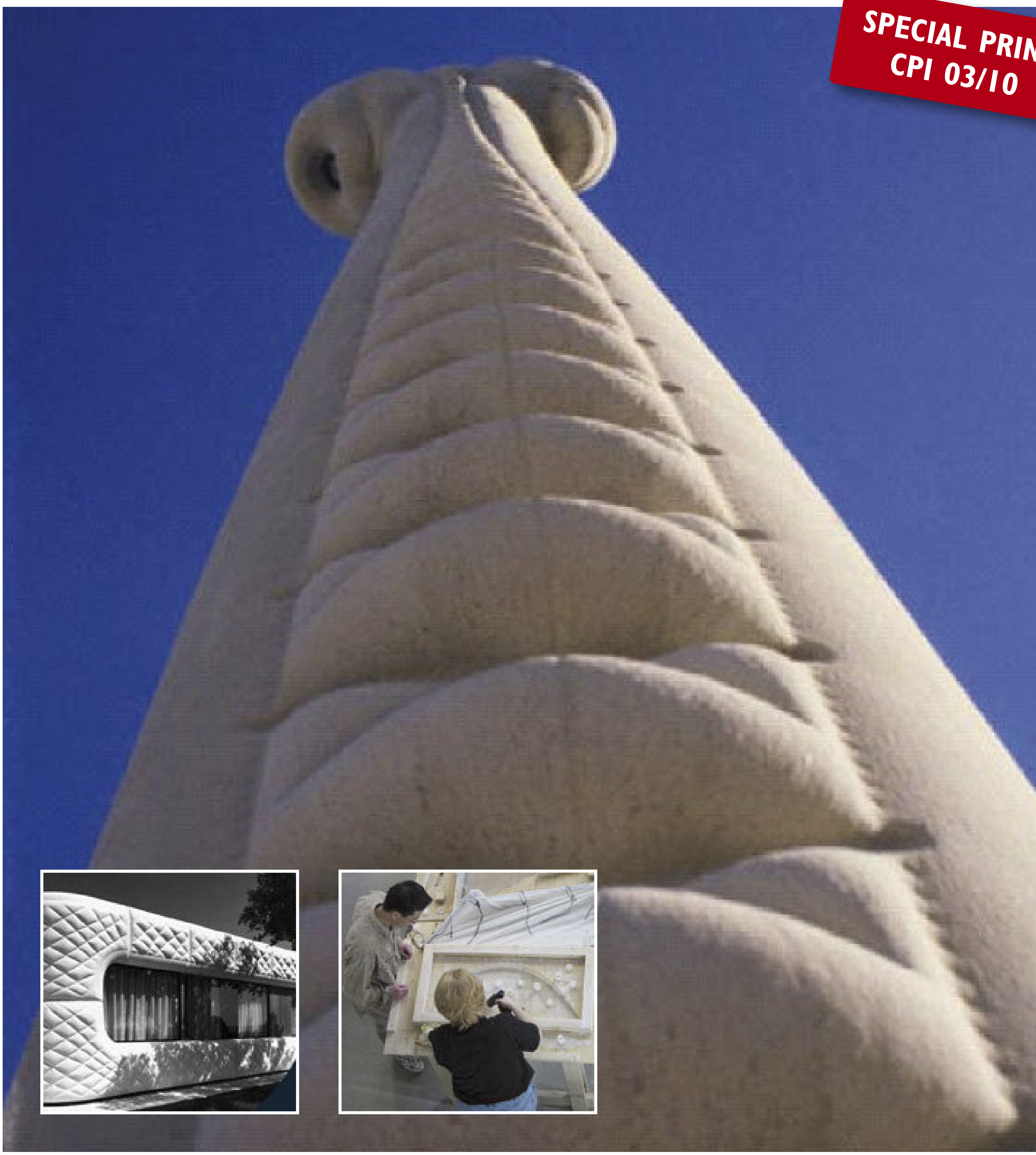


Innovative precast concrete manufacture

Fabric forms for architectural concrete

This article focuses on fabric formworks for use in forming concrete members used in architectural works but it should be kept in mind that this versatile means of containing concrete saw some of its first use in civil engineering works such as erosion control. Concrete members for architectural works have traditionally been cast using a rigid formwork in some desired arrangement ever since men first sought to contain early forms of mortar and "concrete" in their structures. And given the need for a mortar or concrete to set and cure properly the use of a flexible formwork might appear to be rather ill-suited for casting any concrete member. But, this method of casting concrete may in fact be used nearly anywhere a rigid formwork is used and is beginning to attract attention as a method of forming concrete members now that strong and inexpensive geotextiles have become available. This article will hopefully pique the reader's interest and leave her/him inspired to think beyond the simple prismatic shape through the use of fabric as a formwork for the construction of concrete members.

■ Robert P. Schmitz, P.E., Wisconsin, USA ■

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" 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 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 (Fig. 2 and 3). Figure 4 shows a residence where a "frame" restraint method was employed using pipes at a slight angle to restrain the fabric and give these walls their own distinct character. In the USA a Vermont Design/Builder, Sandy Lawton, has used geotextiles to form the columns, walls and floors for a nontraditional "treehouse" which was completed in 2007 (Fig. 5). See the Picasa website (http:// picasaweb.google.com/arrodesign) for construction and completed project photos of this truly unique application using fabric formwork.

Foundations, continuous and spread footings and piers (or columns), have also benefitted from the use of flexible fabric systems. 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'.

These are several of the examples where a flexible fabric formwork has been put to practical use forming architectural applications. Fabric forming applications include:

- Walls
    - o Cast-in-place
    - o Precast
        - Shotcrete thin-shell curtain wall systems
- Beam and floor systems
    - o Trusses
- Columns
- Vaults
    - o Prefabrication of thin-shell funicular compression vaults

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

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

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

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

Fig. 5. "Treehouse" for Chuck and Wendy Black (Sandy Lawton photo)

- Molds for stay-in-place concrete formwork pans
- Foundations
  - Continuous and spread footing systems
- Civil engineering works
  - Revetments, underwater pile jackets and pond liners
  - Coastal and river structures

While it's 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. ACI (American Concrete Institute) 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. It is hoped that standards and guidelines for using flexible fabric formworks will be developed in a timelier manner for the design community to take full advantage of this method of forming concrete members.

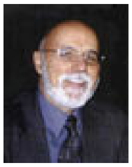
Countries with schools of architecture and engineering with students conducting research include the United States, Canada, England, Scotland, Mexico, Chile, Belgium and the Netherlands. The most prolific research currently being conducted is under the direction of Professor Mark West, Director of the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

Basic principles

The author's first introduction to flexible formwork came from reading an article by Professor West [1]. A visit to C.A.S.T. in June of 2004 exposed the author to this most 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 [2, 3].

The shape a wall panel could take was first explored using a plaster model with various interior support and perimeter boundary conditions (Fig. 6). 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. 7). 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. 8) and the flexible fabric material was pre tensioned at the perimeter (Fig. 9). 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. 10). Reinforcement added to the panel only served to hold it together and was not designed for any particular loading condition for the completed panel (Fig. 11).



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Geotextile fabric as a formwork has a number of 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 and 12)

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.

Engineering complex forms

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

Fig. 6. Model wall panel formwork (C.A.S.T. photo)

Fig. 7. Completed wall panel plaster casts (C.A.S.T. photo)

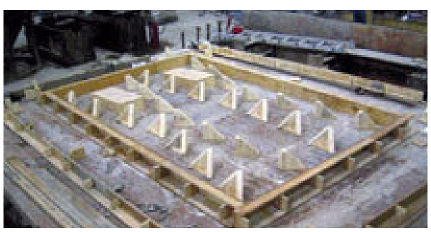

Fig. 8. Placing blockouts and interior supports prior to stretching in fabric in full scale wall panel formwork (C.A.S.T. photo)

Fig. 9. Securing fabric and placing reinforcement in full scale wall panel formwork (C.A.S.T. photo)

efficiency and appearance as a basis for the anchor locations.

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. Prior to a thesis (2004) and a paper (2006) 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 [4,5].

A four step procedure for analytically modeling a fabric formwork was developed employing the structural analysis program ADINA to analyze the formwork and the concrete panel cast in it [6]. 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.

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. *

(* See addendum for additional information.)

International research

While the list of countries conducting research into the use of fabric as a formwork for architectural works continues to grow, the research at C.A.S.T. has been the most innovative and pioneering effort the author has seen to date. Their research centers on the development of new technologies for forming concrete structural members using fabric formworks. They seek to:

- Find new simple and efficient forming strategies using standard tools and fasteners for all the architectural applications mentioned above.
- Develop strategies that not only lead to an aesthetically pleasing structural form but that are efficient and sustainable as well.
- ".... make these new technologies available to both high and low capital building cultures." (C.A.S.T. brochure)

Fig. 10. Placing concrete in full scale wall panel formwork (C.A.S.T. photo)

Fig. 11. Completed concrete wall panels (C.A.S.T. photo)

Fig. 12. Filtration of excess water and air bubbles through geotextile fabric (C.A.S.T. photo)

In addition to the fabric-formed precast concrete wall panels previously mentioned they have explored and continue to explore fabric-formed beams, trusses, columns, vaults and shotcrete thin-shell curtain wall systems.

C.A.S.T. students explore full-scale construction techniques by first modeling them in plaster and then casting them in concrete at full-scale. And as part of the engineering research being done at C.A.S.T., PhD students are conducting structural tests on variable section beams and trusses as well (Fig. 13). Variable section beams by using less concrete than an equivalent rectangular beam can offer substantial savings in the amount of materials required for construction contributing to a more efficient and sustainable design.

Simple, flat rectangular sheets of fabric are also being used to explore the shapes columns might take (Fig. 14). And while structural efficiency may not play a major role in their design their appearance is anything but boring as they can take on a very sculptural look.

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. Their 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.

Fabric sheets are allowed to deflect into naturally occurring funicular geometries, producing molds for lightweight funicular compression vaults and double curvature wall panels. Fig. 15 to 17 show the process of taking that pure funicular tension geometry and inverting it to produce pure funicular compression geometry, a most efficient structural shape. It should be noted here however, that in order for the compression vault to carry a uniform load the fabric formwork membrane must also be loaded uniformly. Other loading conditions can be accommodated by altering the membrane's geometry accordingly.

Creating formwork intended for thin-shell GFRC stay-in-place formwork pans for CIP floor slabs or thin-shell funicular compression vaults also shows great promise. The use of GFRC stay-in-place formwork pans for a CIP floor slab system allows the slab to span between integral support beams in pure compression. The reduction of construction materials including concrete and reinforcement along with a reduction in the deadweight of the system all help to contribute to structural sustainability.

Fabric-formed rigid molds required the production of a new fabric that allows concrete to adhere to one side but not the other. High density fabrics woven from polyethylene or polypropylene can be manufactured with a smooth coating on one side and a fuzzy non woven fabric welded to the other. Concrete placed against the smooth coated side will release without the use of release agents but adhere to the fuzzy non woven side (Fig. 18).

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. 19 and 20). Using a carbon fiber grid in lieu of conventional reinforcing steel allows for a creation of a very thin section – only 3cm (1.2 in.) thick (Fig. 20). The completed vault, as shown in Figure 21, would certainly enhance the appearance of any enclosed space. C.A.S.T. has created a number of variations in vault construction using this fabric formed approach (see their website for further information).

The engineering of these complex and exotic vault 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 [7]. 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.

Fig. 13. Testing of variable section concrete truss (C.A.S.T. photo)

Fig. 14. Completed full scale column (C.A.S.T. photo)

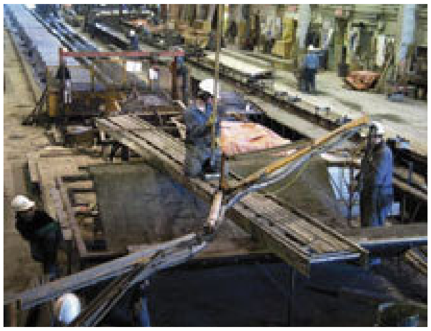

Fig. 15. Step 2- Uniform layer of GFRC is applied (C.A.S.T. photo)

Fig. 16. Step 3 – Resulting funicular shell is inverted to form mold (C.A.S.T. photo)

Fig. 17. Step 4 – Thin-shell funicular GFRC vault produced from mold (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.

Conclusions and further research

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

- The forming of very complex shapes is possible
- Geotextile fabric is strong, lightweight, inexpensive and is reusable
- 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

Fig. 20. Placing concrete and carbon grid in fabric mold to form double curvature funicular thin-shell vault (C.A.S.T. photo)

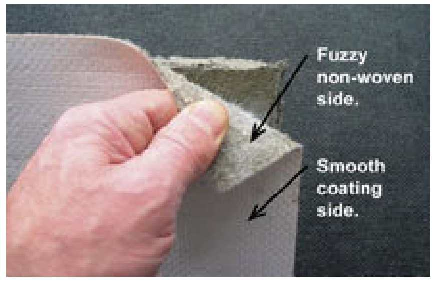

Fig. 18. Fabric for forming rigid molds (C.A.S.T. photo)

Readers interested in additional information are encouraged to visit the websites listed under 'Further information' especially, the C.A.S.T. website at the University of Manitoba where numerous examples and literature on this topic may be found.

Further information

- Author's web site dedicated to research on this topic: www.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/
- Fab-Form Industries, Ltd., Surrey, British Columbia, Canada: http://www.fab-form.com/
- Monolithic (air inflated domes), Italy, Texas: http://www.monolithic.com/

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[1] West, M., (October 2003), "Fabric Formed Concrete Members", Concrete International Vol. 25(10), pp 55-60.

[2] West, M., (April 2002), "Prestressed Fabric Formworks for Precast Concrete Panels", Materials Technology Workshop, Department of Architecture, University of Manitoba, Canada., Web address: http://www.umanitoba.ca/cast_building/resources.html

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[7] EOS Systems, Inc. PhotoModeler® Scanner (Version 6.3.3). [Computer program]. Available: EOS Systems, Inc., 210-1847 West Broadway, Vancouver BC V6J IY6 Canada. April 22, 2009.

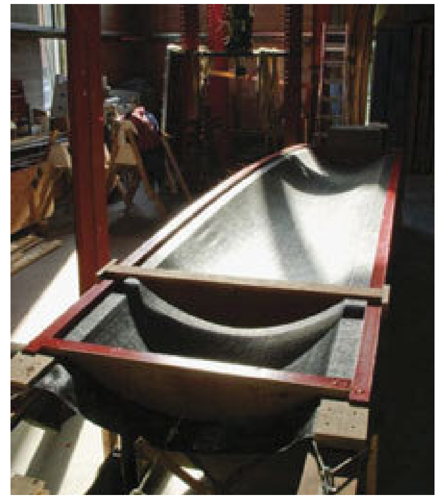

Fig. 19. Fabric mold stretched lengthwise in frame to form double curvature funicular thin-shell vault (C.A.S.T. photo)

Fig. 21. Completed double curvature funicular thin shell vault (C.A.S.T. photo)

ADDENDUM

Due to editorial constraints two figures from the section on ***Engineering complex forms*** and text from the section on ***Conclusions and further research*** was omitted. Those figures and that text are provided here for your information.

Figure A1 was referenced in the second paragraph of the section on **Engineering complex forms** and in the line *"A procedure to "form-find" and analyze the complex panel shape is required."*

Figure A2 was referenced in the last line of paragraph three in this section and in the line *"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."*

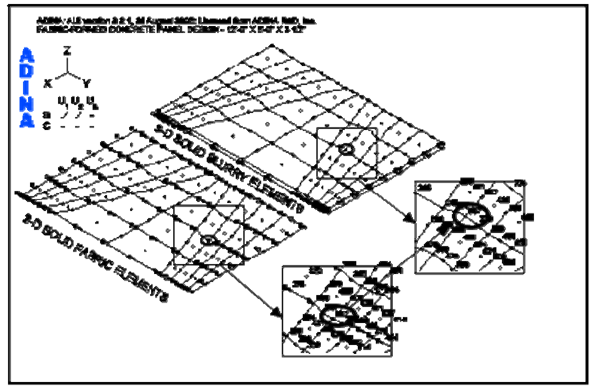

Fig. A1. Form-finding concrete panel shape using finite element analysis (FEA).

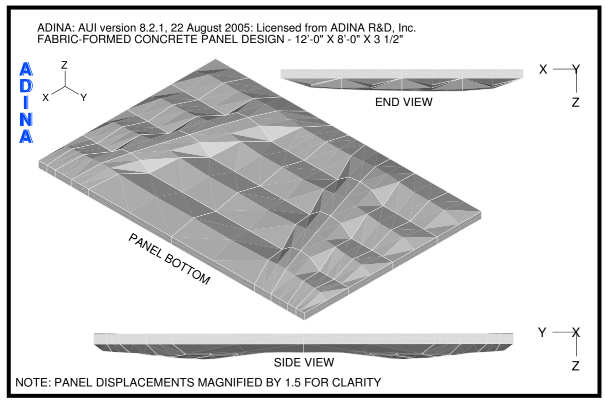

Fig. A2. Final concrete panel shape using FEA.

In addition, the following bullet points discussing further research were omitted from the section ***Conclusions and further research.***

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.

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