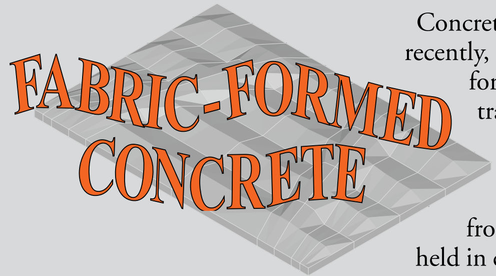
FABRIC-FORMED CONCRETE



Concrete members have traditionally been cast using a rigid formwork. Although recently, ACI Committee 334 has introduced construction of shells using inflated forms. Straightforward methods of analysis and design are available for the traditionally cast concrete member – be it a concrete floor, beam, wall or column member.

To date, no design procedures or methods to predict the deflected shape of a fabric cast concrete member have been developed. This article, adapted from a paper presented at the 17th *Analysis & Computation Specialty Conference* held in conjunction with the *2006 Structures Congress*, introduces a design procedure that allows one to design a fabric cast concrete wall panel.

By Robert Schmitz, P.E., M. ASCE

Figure 1: Model formwork and completed plaster casts. Courtesy of C.A.S.T.

The use of a flexible formwork appears to be ill suited for casting any concrete member since the way concrete has traditionally been cast has been in an all-rigid formwork. This method of casting concrete may in fact be used anywhere a rigid formwork is used and is beginning to attract attention as a method of construction. An article by Mark West, Director of the Centre for Architectural Structures Technology (C.A.S.T.) at the University of Manitoba, Canada, published in *Concrete International* was the author's first introduction to flexible formwork (West, 2003). For the past several years, 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 members (*Figure 1*) (West, 2002, West, 2004).

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 2*).

Figure 2: Full-scale formwork and completed concrete panel. Reinforcement, added to the panel, only served to hold it together and was not designed for any particular loading condition. Courtesy of C.A.S.T.

Proposed Design Procedure

A four-step procedure is proposed that allows one to design a fabric cast concrete panel. For demonstration purposes, a 12-foot long by 8-foot wide by 3½-inch thick wall panel will be designed for self-weight and a ±30 psf lateral wind load using a concrete strength of 5,000 psi. These steps are:

1) Determine the paths the lateral loads take to the points where the wall panel is to be anchored. *Figure 3* shows a summary of the load paths obtained from a finite element analysis (FEA) study for various panel anchor arrangements. For our example, anchor arrangement BC3 will be used.
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. These elements are arranged to define the panel's lines of support (*Figure 4*). Interior supports are indicated by a "B" in this figure. The fabric will deflect between these interior supports, creating thicker panel regions capable of resisting more load than at the supports where it remains at its initial thickness. These deflected regions define the panel's load paths. Increased strength will be provided spanning the width of the panel along a diagonal path, for a 4-point anchor condition, due to these thickened regions.
3) "Form-find" the final shape of the panel by incrementally increasing the thickness of the 3-D solid elements until equilibrium in the supporting fabric formwork has been reached (*Figure 5*). This iterative process proceeds as follows:
    a) Run the model under slurry gravity loading and determine the interior fabric element node displacements.
    b) Increase the 3-D element thicknesses at each interior node (e.g., at node 357, *Figure 5*) by the amount the fabric displaces (e.g., at node 367, *Figure 5*). The bottom node remains stationary, while the top and mid-level nodes are adjusted upward. (The computer model panel is formed in reverse of how it would occur if the slurry were actually being poured into the fabric formwork.)
    c) Rerun the model and determine the interior fabric element node displacements.
    d) Repeat Steps b-c until displacements between the last two runs are within a tolerance of approximately 1%. This is equivalent to achieving a flat surface in the actual concrete panel.
4) Analyze and design the panel for strength requirements to resist the lateral live load, and self-weight dead load being imposed upon it, by replacing the slurry material model with a concrete material model. For dead load; $P_{uD} = 1.2 \times D_c$, where D_c is the density of the concrete panel, and live load; $P_{uW} = 1.6 \times 30$ psf = 48 psf.

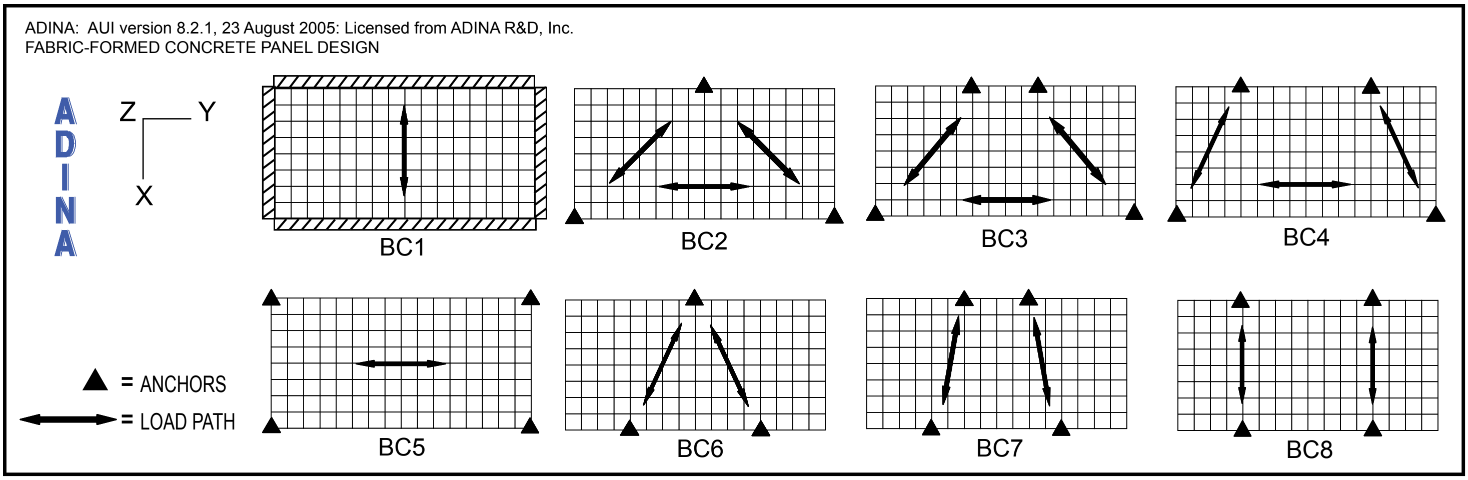


Figure 3: Panel load paths and anchor locations.

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. Obtaining an optimal panel shape is possible using an iterative process.

Analysis Methodology and Materials

Model development and analysis of the fabric cast concrete panel is performed utilizing the structural analysis/finite element program ADINA (ADINA, 2004, ADINA, 2004a). Efficient modeling plays an essential role in the development of this finite element model. The elements making up the supporting fabric formwork and the elements, which eventually make up the final concrete panel shape, are defined in the same model. Once the final concrete panel shape is defined by using an iterative "form-finding" technique, the fabric elements are discarded. The concrete panel elements are then designed for the appropriate lateral loads under the given set of boundary conditions.

The difficulty with combining the two element types required to define the overall model is that they each have their own material properties, which can contribute to the overall strength and stiffness of the model. Initially, the concrete is plastic and is considered fluid in nature, similar to slurry. The slurry will contribute weight to the fabric element portion of the model but cannot contribute stiffness to it. Therefore, an intermediate step is required. In this step, the slurry – characterized as a material that has weight, but no strength or stiffness – is used as the material property for the concrete panel elements while the panel shape is being found.

Model material properties

The fabric material is anisotropic. The modulus of elasticity is different in the WARP (machine direction, along the length of the roll) and the FILL (cross-machine direction, through the width of the roll), as seen in *Figure 4*. These differences are important when modeling the fabric, as well as for securing it to the supporting formwork. The fabric in this model was prestressed 2% across the panel length, and as a result of relaxation effects, its modulus of elasticity required a reduction of 50%. Mechanical properties for geo-textile fabrics are obtained from stress-strain curves developed in accordance with the standard test methods of ASTM D4595 (ASTM, 2001). Stress-strain and relaxation data for the Amoco 2006 geotextile fabric were obtained from the Amoco Fabrics and Fibers Company (Baker, 2002, Baker, 2005).

The slurry material, as stated above, must not contribute stiffness to the fabric element portion of the computer model. As a result, a very low modulus of elasticity (E_{sm} = 2 psi) must be used for this elastic-isotropic material (*Figure 4*). The slurry's density will function as a mass-proportional load on the surface of the fabric element.

Analysis Results

The panel will be analyzed using the strength design method for plain concrete and ACI 318-02, Section 22 (ACI, 2002). The governing criterion for structural plain concrete design is the uniaxial cut off strength of the concrete or Modulus of Rupture as stated in Section 22 of ACI 318-02. Maximum principal tensile stresses resulting from positive and negative wind loads combined with gravity loads must fall below this value, which for 5,000 psi concrete is 353.6 psi. When the maximum principal tensile stress is greater than the Modulus of Rupture, the ADINA model indicates this point by a "crack" in the panel model. The *ADINA Theory and Modeling Guide* notes: "…for concrete…these are true principal

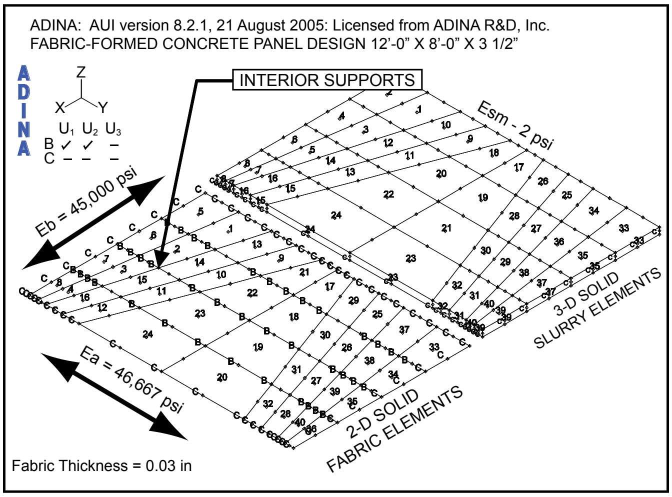


Figure 4: Combined fabric and slurry model.

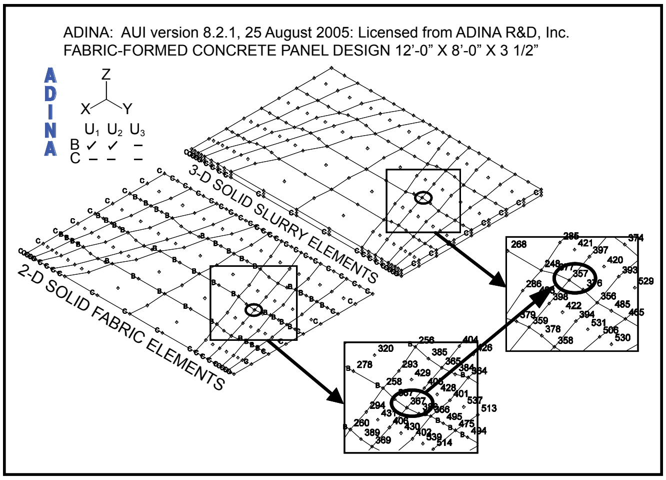


Figure 5: "Form-finding" combined fabric and slurry model.

stresses only before cracking has occurred. After cracking, the directions are fixed corresponding to the crack directions and these variables are no longer principal stresses" (ADINA, 2004a). ADINA uses a "smeared crack" approach to model the concrete failure.

Following are summary graphic output and results for the panel under investigation.

Figure 6 shows the results of "form-finding" the shape for the panel under consideration.

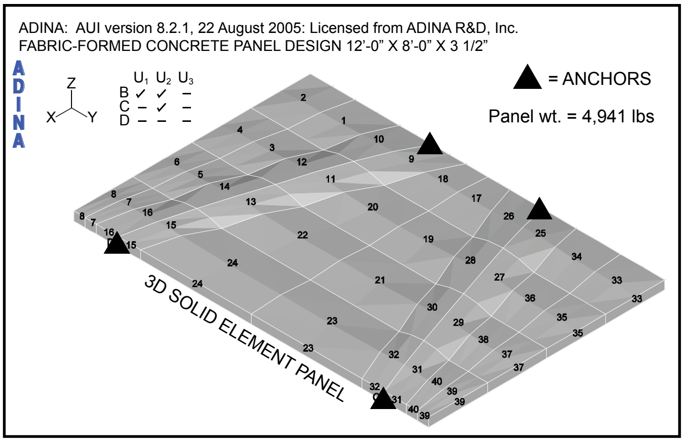


Figure 6: Panel model.

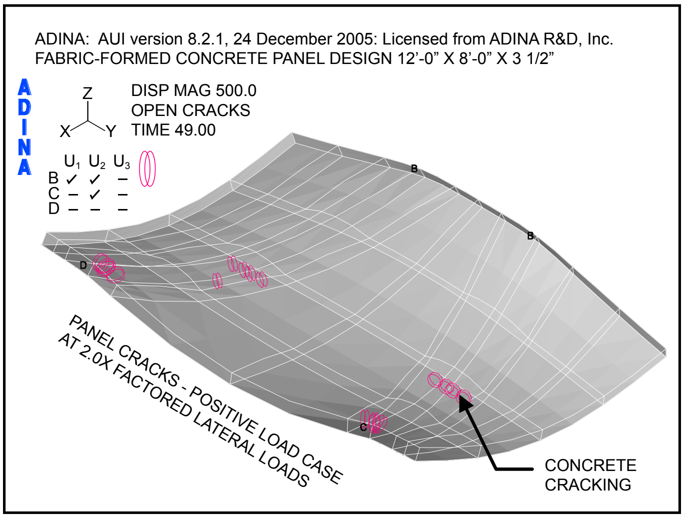


Figure 7: First panel cracks, back.

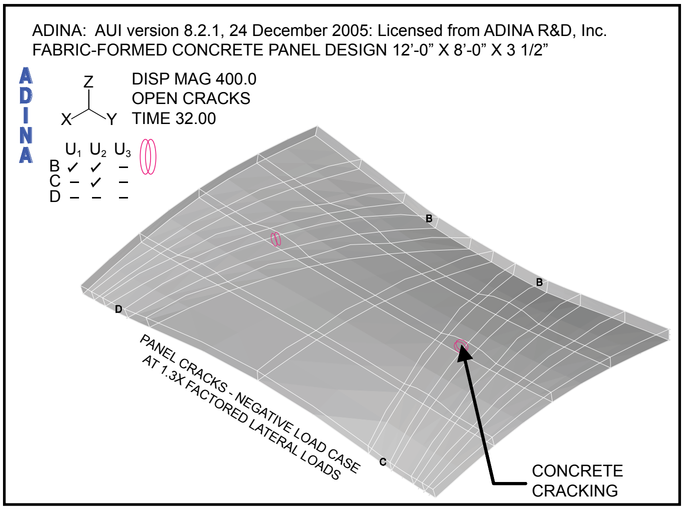


Figure 8: First panel cracks, front.

The finite elements are arranged in a pattern that follows the fabric formwork design shown in *Figure 4 (see page 13)* and are supported with a 4 point anchor arrangement. After "form-finding", the final weight of the panel is 4,941 lbs.

Figures 7 and *8* show the loading conditions under which the panel first cracks. For case two, the negative load case, the first cracks occur at 1.3-times the factored load as shown in *Figure 8*. For case one, the positive load case, the panel does not crack, *within the body of the panel*, until 2 times the factored positive load is reached, as shown in *Figure 7* – local cracking at the supports being ignored.

The reason for this rather curious effect may be explained by observing the compressive principal stress at a section cut along the diagonal load path as shown in *Figure 9*. This figure 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. This effect is not observed under the negative lateral load case. The benefit of the funicular tension curves in the fabric formwork, which produced this panel shape, is evident.

Figure 10 shows a maximum principal tensile stress of 193 psi for the positive lateral load case at the factored load. Load paths between the supports are indicated by the double headed arrows. This corresponds to the load path for Panel BC3 shown in *Figure 3 (see page 13)*. A maximum principal tensile stress of 289 psi was found for the negative lateral load case at the factored load.

Reinforcement Considerations

The results of a plain concrete analysis for the panel under consideration show that a minimum panel thickness of 3½ inches is adequate. This panel has a maximum thickness of 5.89 inches and an equivalent uniform thickness of 4.26 inches. While this panel has achieved an optimal form, it is slightly "over-strength". Ideally, first panel cracks should occur just as the factored design load is reached.

For a "real world" design, reinforcement would be required. Selective reinforcement in the regions where the principal tensile stresses are greatest may be all that is required. And while full-scale panel testing would be required, the benefits of having a more efficient panel design might well be worth the effort.

Conclusions and Future Research

The procedures introduced in this article provide an efficient method for the analysis and design of a flexible fabric formwork and the resulting complex concrete panel shape thus formed. The slurry material model used with the 3-D solid finite element proves very helpful in saving FEA modeling time by allowing the panel shape to be formed, and then later analyzed by simply substituting a concrete material model for the slurry material model and without re-meshing the FEA model. The potential benefits for using a flexible fabric formwork include:

- Geotextile fabric is strong, lightweight and inexpensive.
- A more efficient design is possible by using less concrete and reinforcing where required.
- Improved surface finish and durability of the concrete product are possible due to the filtering of air bubbles and excess bleed water through the geotextile fabric.
- Very complex shapes are possible, which increases freedom of design expression.

The advancement of fabric-formed concrete member design would be furthered by:

- The development of computer software which would automatically "form-find" the panel shape and then allow it to be analyzed.
- Design verification by analysis and testing of full-scale wall panels.
- Investigating the role creep plays in the geotextile fabric formwork during the design process.
- Development of new fabrics, with improved properties over those of geotextile fabrics, for use as flexible formworks.

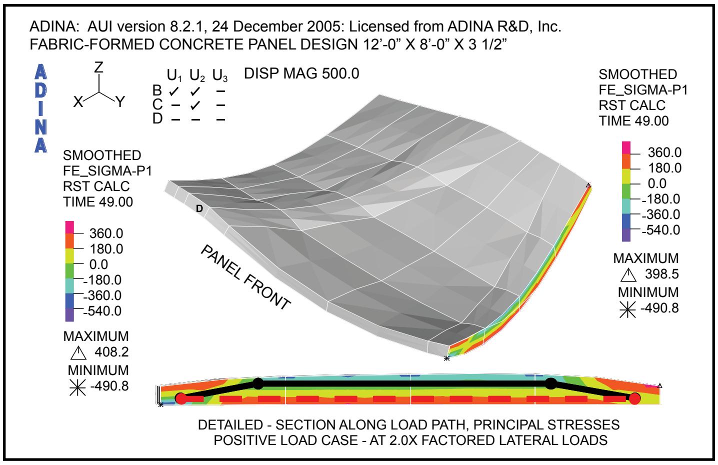


Figure 9: Principal stresses at section cut.

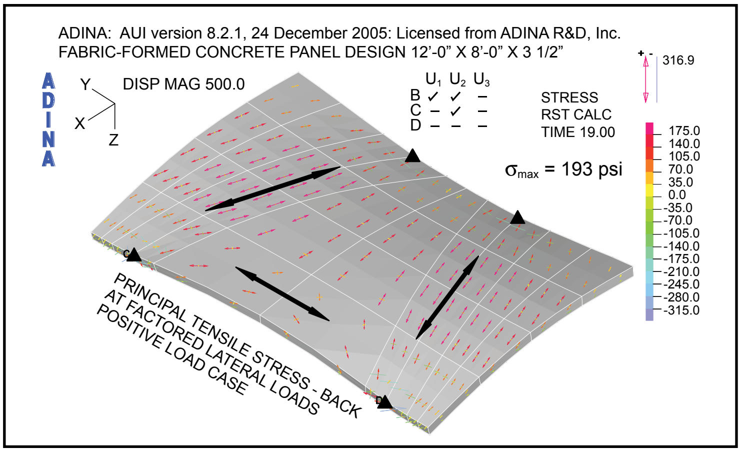


Figure 10: Panel principal stresses, back.

- Investigation of concrete panel reinforcement options such as fiberglass rebar, alkali resistant (AR) glass textile and carbon fiber grids.

At the recent 1st International RILEM Conference Textile Reinforced Concrete (ICTRC) held at RWTH Aachen University in Aachen, Germany, the author had the opportunity to present a paper on the use of fabric-formed concrete. As a new application, fabric-formed concrete appears to be well-suited to use "technical" textiles for reinforcement as well. The two and three-dimensional glass textiles being developed at Aachen and Dresden Universities are very exciting and hold great potential for use in fabric-formed concrete. Individuals or universities interested in developing cooperative efforts to further this research are encouraged to contact the author of this paper.▪

A full version of this paper may be found in the *Proceedings of the 17th Analysis and Computation Specialty Conference on the Structures Congress 2006 CDROM,* available from ASCE.

*Robert Schmitz, P.E., M. ASCE, is a Structural Engineer and President of RP Schmitz Consulting Engineers, LLC located in Brookfield, WI. For additional information see the website **www.fabric-formedconcrete.com** or contact Robert at **rpschmitz@rpschmitz.com**.*

The on-line version of this article contains detailed references. Please visit **www.STRUCTUREmag.org**.

References

ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318 02)* and Commentary (ACI 318R 02). Farmington Hills, Michigan: American Concrete Institute, 2002.

ADINA R & D, Inc. *ADINA* (Version 8.2.1). [Computer program]. *Available*: ADINA R & D, Inc., 71 Elton Avenue, Watertown, Massachusetts 02472, September 2004.

ADINA R & D, Inc. *ADINA – Theory and Modeling Guide*. Report ARD 04 7. Available: ADINA R & D, Inc., 71 Elton Avenue, Watertown, Massachusetts 02472, September 2004a.

ASTM International. ASTM Committee D35 on Geosynthetics. *Test Method for Tensile Properties of Geotextiles by the Wide Width Strip Method*, Designation: D 4595 86 (Reapproved 2001). In Annual Book of ASTM Standards 2001. Vol. 4.13: Geosynthetics. West Conshohocken, Pennsylvania: ASTM International, 2001, pp. 1 10.

Baker, T. *Amoco 2006 Stress Strain*. Atlanta, Georgia: Amoco Fabrics and Fibers Company, 2002. [Internet, e mail to the author].

Baker, T. *Amoco 2006 Relaxation Results*. Atlanta, Georgia: Amoco Fabrics and Fibers Company, 2005. [Internet, e mail to the author].

West, M. "Fabric Formed Concrete Members." *Concrete International* Vol. 25(10), October 2003, pp. 55+.

West, M. "Fabric Cast Concrete Wall Panels." Materials Technology Workshop, Department of Architecture, University of Manitoba, Canada, April 2002. [Internet, WWW]. Address: **http://www.umanitoba.ca/faculties/architecture/cast/CASTonline.html**

West, M. "Prestressed Fabric Formwork for Precast Concrete Panels." *Concrete International* Vol. 26(4), April 2004, pp. 60+.