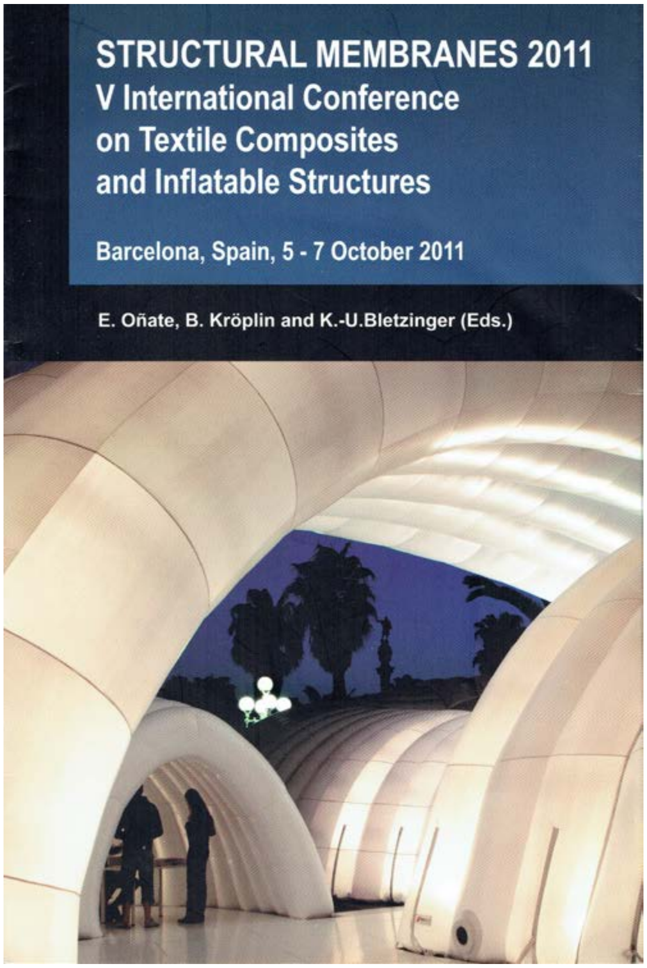
FABRIC-FORMED CONCRETE MEMBER DESIGN

Author:
Robert P. Schmitz, P.E.
RPS STRUCTURAL ENINEERING, LLC
Brookfield, WI 53045-5504
Phone: 1-262-796-1070
E-mail: rpschmitz@rpschmitz.com
Web Sites: http://www.rpschmitz.com
http://www.fabric-formedconcrete.com
http://www.fabwiki.fabric-formedconcrete.com



International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2011
E. Oñate, B. Kröplin and K.-U.Bletzinger (Eds)

FABRIC-FORMED CONCRETE MEMBER DESIGN

ROBERT P. SCHMITZ, P.E.

RPS Structural Engineering, LLC
357 Terrace Drive East, Brookfield, Wisconsin 53045, USA
e-mail: rpschmitz@rpschmitz.com, web sites: http://www.rpschmitz.com
http://www.fabric-formedconcrete.com, http://www.fabwiki.fabric-formedconcrete.com/doku.php

Key words: Fabric-formed, flexible, concrete, form-finding, concrete formwork.

Summary. *This paper introduces engineering design and analytical modeling techniques providing the design community with an alternative means for forming concrete structures by using flexible fabric formwork.*

1 INTRODUCTION

Since its invention by the Romans, concrete has been cast into all manner of formworks whether temporary or permanent. All-rigid formworks 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.

The American Concrete Institute's Committee 347[1] (ACI) formally introduced the first standard guide for the design and construction of formwork in 1963. And, it was only recently (2005) that ACI Committee 334[2] introduced a standard guide for the construction of shells using inflated forms even though several methods of construction using inflated forms[3] have been available since the early 1940's. It can take many years to standardize methods of construction today regarded as experimental.

One such experimental and imaginative means of construction is the use of a flexible formwork that, while not inflated, still gives form to structural members previously cast in only all-rigid formwork. 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 yet casting concrete into flexible formworks may in fact be used nearly anywhere a rigid formwork is used.

As a means for forming concrete this versatile way of containing concrete saw some of its first use in civil engineering works such as erosion control and now that strong, inexpensive geotextiles have become available it is also beginning to attract attention throughout the world for architectural and structural applications. Architects and designers in Japan, Korea, Canada and the United States have begun to use flexible fabric formworks made from geotextile fabric to form concrete members for their projects. However, a significant amount of research remains to be done to bring these forming systems into everyday practical use by the construction industry.

Standards and guidelines for using flexible fabric formworks need development in a timely manner so that the design community can take full advantage of this means for forming concrete members. This paper focuses on the engineering aspects involved in designing a precast concrete panel member, just one of numerous concrete member types used in architectural and structural works where fabric formworks may be used.

1.1 Research efforts

The author's first introduction to flexible formwork came from reading an article by Mark West, Director of the Centre for Architectural Structures and Technology (C.A.S.T.) at the University of Manitoba, Canada, published in *Concrete International*[4]. Canada is one of a number of countries with schools of architecture and engineering where students conduct research into this unique means of forming concrete. Other countries include the United States, England, Scotland, Mexico, Chile, Belgium and the Netherlands.

Architectural students at C.A.S.T.[5, 6] explore the use of flexible formwork using cloth fabric and plaster before creating a full-scale cast of a concrete panel. 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 1.

Figure 1: Model formwork and completed plaster casts (C.A.S.T. photos)

The casting of a full-scale panel using concrete requires finding a fabric capable of supporting the weight of the wet concrete. Ideally suited for this purpose are geotextile fabrics. These fabrics made of woven polypropylene fibers are low cost and have a high tensile strength component. The flexible fabric material is pre-tensioned in the formwork over interior supports where required to give the panel its desired aesthetic form. Geotextile fabric as a formwork material has a number of 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.

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, accelerated by an increase in temperature as might occur during hydration of the concrete as it cures.
- The concrete requires careful placement and the fabric formwork must not be jostled while the concrete is in a plastic state.

The author believes however, the benefits of using geotextiles far outweigh any disadvantages until new fabrics are developed. Among the key benefits are economies of construction, durability of the product and freedom of design expression.

Figure 2 shows the interior supports for a full-scale formwork prior to stretching in the fabric membrane and the resulting completed concrete panel.

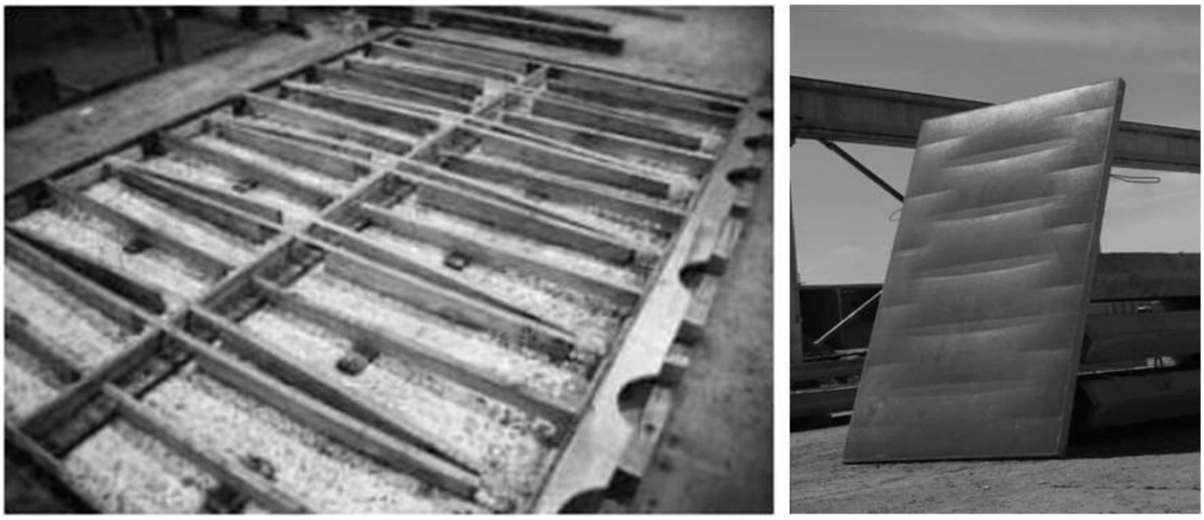


Figure 2: Full-scale formwork and completed concrete panel (C.A.S.T. photos)

For illustration purposes, an unreinforced 12’-0” long x 8’-0” wide x 3½”–thick (3.7 m x 2.4 m x 88.9 mm) wall panel will be designed for self-weight and a ±30 psf (±1.44 kPa) lateral wind load using a concrete strength of 5,000 psi (34.5 MPa).

1.2 A design procedure

Due to the complex structural shapes wall panels can take when formed in this manner the challenge is finding an appropriate method of analysis. Straightforward methods of analysis and design are available for the traditionally cast concrete column, floor beam, and wall or floor panel. Shapes as complex as these require the use of finite element analysis (FEA) software and a procedure to “form-find” and analyze the complex panel shape is required. Prior to a thesis[7] and a paper[8] by the author, to introduce a design procedure, analysis methods to predict the deflected shape of a fabric cast panel were unavailable.

We introduce a four-step procedure for analytically modeling a fabric formwork employing the structural analysis program ADINA[9, 10] to analyze the formwork and the concrete panel cast into it. The final panel form, function and performance of the fabric membrane and the reinforcement of the panel for design loads all add to the complexities of the panel's analysis and design. The four steps in this procedure are as follows:

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

If, after a completed analysis of the panel in Step 4, it is found that the panel is either "under-strength" or too far "over-strength", adjustments to the model in Step 2 will be required and Steps 3 and 4 repeated. With this iterative process, it should be possible to obtain an optimal wall panel design. Prior to implementing this four-step procedure, however, the modeling techniques utilized in Steps 2 and 3 above require defining.

2 MATERIAL PROPERTIES AND ANALYSIS METHOD

Efficient modeling plays an essential role in the development of the finite element model. The finite 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 considered fluid in nature, similar to a 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.

2.1 Fabric model material properties

The geotextile fabric material, used as the supporting formwork, 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) directions. These differences are important when modeling the fabric as well as for securing it to the supporting formwork. Mechanical properties for geotextile fabrics are obtained from stress-strain curves developed in accordance with the standard test methods of ASTM D4595[11].

Stress-strain data for the Amoco 2006 geotextile fabric obtained from Amoco Fabrics and Fibers Company[12] allowed the properties shown in Table 1 for this elastic-orthotropic material to be entered into the ADINA material model. There is little interaction between the two perpendicular directions in a woven fabric and a value of zero for Poisson's Ratio was chosen for this material model[13].

t = 0.03-in (0.762 mm)	Fabric thickness
$E_{warp} = E_a$ = 46,667 psi (321.8 MPa)	Modulus of Elasticity, Machine Direction
$E_{fill} = E_b$ = 90,000 psi (620.4 MPa)	Modulus of Elasticity, Cross Machine Direction
G = 23,333 psi (160.6 MPa)	Shear Modulus
$\nu = 0.0$	Poisson's Ratio

Table 1: AMOCO 2006 geotextile fabric material properties

Relaxation can occur due to the prestress forces in the membrane and there is the potential for creep in the geotextile material. Geotextile fabrics are temperature sensitive, and as a result, creep as the temperature increases[14]. Creep may be more of a factor as the concrete panel cures due to the heat of hydration than initially as the concrete is being poured into the fabric formwork.

The effects of creep in the geotextile fabric are not included in this paper but relaxation will be considered in the modeling of the fabric panel. Loss of prestress due to relaxation of the fabric can exceed 50% after just a 20-minute period depending on the percentage of initial prestress and the direction in which the fabric is prestressed[15].

2.2 Slurry model material properties

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 must be used for this elastic-isotropic material. The slurry material will function as the load on the fabric element model using the slurry's density as a mass-proportional load. Table 2 summarizes the slurry material properties used in the ADINA material model.

t = varies-in (mm)	Slurry thickness
E_{sm} = 2 psi (13.79 kPa)	Modulus of Elasticity
$\nu_{sm} = 0.0$	Poisson's Ratio
$D_{sm} = 2.172 \times 10^{-4}$ lb-sec^2/in^4 (2,321 kg/m^3)	Density

Table 2: Slurry material properties

2.3 Step 1 – Determination of load paths

In the first step, a FEA study of a uniformly thick panel with various boundary conditions is performed in order to determine the load paths an applied lateral load might take. A distributed unit load is applied to a series of panels using 3-D solid elements and the resulting principal stresses examined. For this study, any uniform material type may be used. Figure 3 shows the results of these panel investigations for a variety of boundary conditions. The double-headed arrows indicate the general direction the maximum principal stresses take.

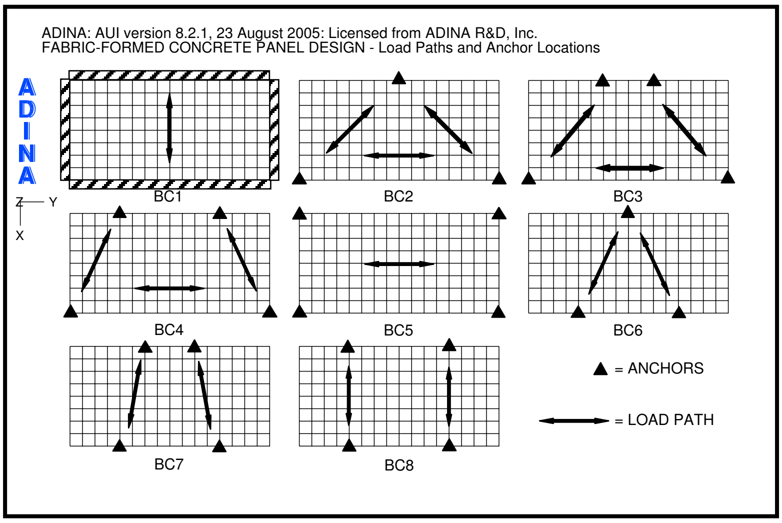


Figure 3: Panel load paths and anchor locations

Note in Figure 3 that panel anchor locations appear to result in load paths, which fall into one of two cases. Load paths defining Case 1 are parallel to one of the panel's edges as shown in Panel BC1, which has a continuous simple edge support, or Panel BC5 and Panel BC8, which have symmetrical 4-point anchor locations. The load paths in the remaining panels appear to triangulate in their direction between the anchor locations and define Case 2. For illustration purposes, the anchor locations shown in **Panel BC3** are assumed – where the load paths triangulate. This anchor arrangement was also chosen for the interesting shape the final panel design takes.

2.4 Step 2 – Define fabric formwork design

Based on the study of the load paths shown in Figure 3, the formwork is laid out and the interior and perimeter boundary conditions are introduced as shown in Figure 4. A **"B"** in this figure indicates location of the interior supports.

The fabric in this model will be laid with the cross machine direction spanning the narrow dimension of the panel and the machine direction spanning along the length of the panel. 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. In addition, "collector" paths are formed along the length of the panel to bring the load to the diagonal load paths.

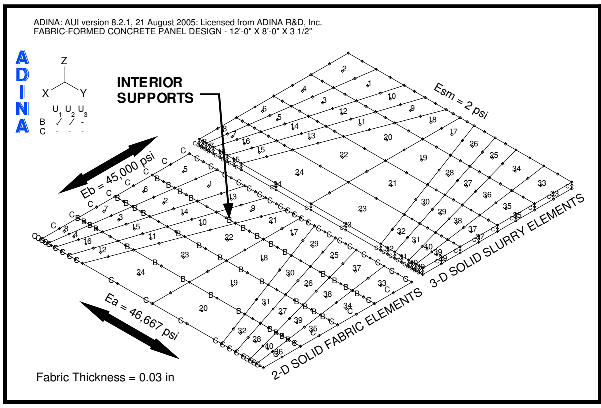


Figure 4: Combined fabric and slurry model (1-in = 25.4 mm, 1 psi = 6.9 kPa)

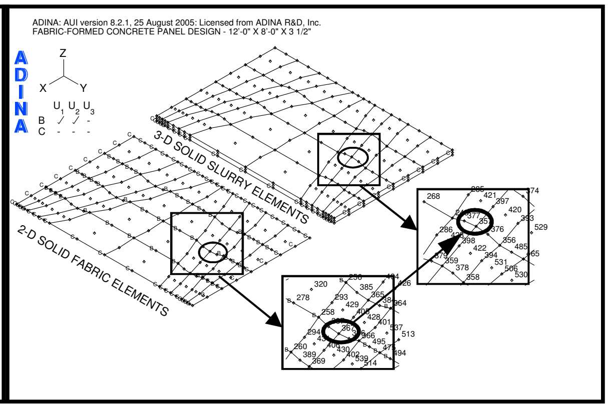


Figure 5: "Form-finding" combined fabric and slurry model

2.5 Step 3 – "Form-finding" the panel shape

The ADINA model representing the supporting fabric formwork in combination with the slurry material, which functions as the load on the formwork is shown in Figure 4. For clarity, the fabric and slurry element groups are shown separately.

The computer model representing the supporting fabric formwork uses 9-node, 2-D solid elements. The 2-D solid element uses a 3-D plane stress (membrane) kinematic assumption. A prestress load of 2% is applied to the fabric in the cross machine direction with a 50% reduction in the modulus of elasticity, E_b, due to relaxation, assuming the concrete is poured within one hour of prestressing the fabric. A one-half percent prestress load is applied in the machine direction to keep the fabric taut with no reduction in E_a being taken. Thus, the modulus of elasticity is approximately equal in each direction. The 2-D solid fabric elements use a large displacement/small strain kinematic formulation.

The computer model representing the slurry material will use 27-node, 3-D solid elements. To be consistent with the 2-D fabric elements, the 3-D slurry elements also use the large displacement/small strain kinematic formulation.

Now that the model is defined, "form-finding" of the panel shape may proceed. Initially, the 3-D slurry elements are uniformly 3½-in–thick (88.9 mm). "Form-finding" the panel shape proceeds as follows:

1. Run the model under slurry gravity loading and determine the interior fabric element node displacements.
2. 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.)

3. Rerun the model and determine the interior fabric element node displacements.

4. Repeat Steps 2-3 until displacements between the last two runs are within a tolerance of approximately 1%.

Given the hundreds or even thousands of interior nodal locations that will require adjustment, depending on the size and complexity of the model, the task of manually adjusting the nodal locations becomes daunting. Fortunately, ADINA can both output displacement information and input nodal locations using text files, which when used with a spreadsheet program greatly facilitates this "form-finding" task. Still, what would be desirable is a program that can automatically update its nodal locations.

The finite element model in Figure 6 shows the results of "form-finding" the panel shape made up of the slurry material. The boundary conditions that created it were illustrated in Figure 4.

2.6 Step 4 – Panel analysis and design

A strength analysis of the panel will need to be performed before any judgment can be made of whether or not the panel is adequate. The panel design may be optimized, to account for over or under-strength, by adjusting the following list of variables and repeating Steps 2-4 of the design procedure.

- Concrete strength
- Initial panel thickness
- Prestress in fabric formwork and
- Anchor locations

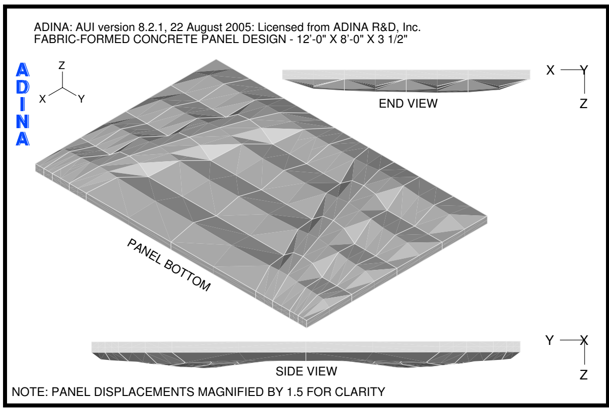


Figure 6: Panel shape after "form-finding"

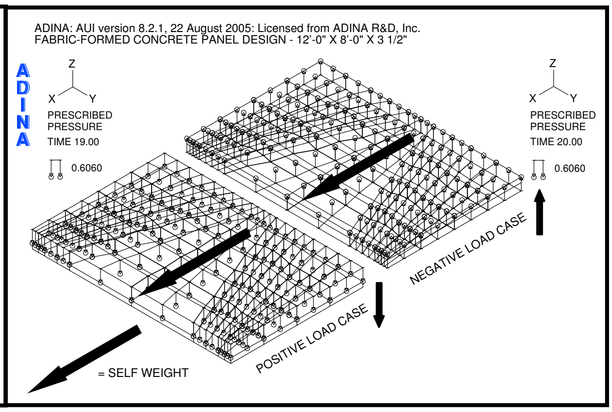


Figure 7: Panel load cases. (1 psi = 6.9 kPa)

The panel shape defined in Figure 6 may now be analyzed for strength under the ±30 psf (±1.44 MPa) design lateral wind load and gravity self-weight. Two lateral load cases are considered, a positive load case and a negative load case as shown in Figure 7. The lateral loads will cause bending in the panel and the gravity loads are in-plane loads that will contribute to membrane action in the vertically oriented panel. The panel will be analyzed using the strength design method for plain concrete and ACI 318-02, Section 22[16].

The properties for the slurry material are now replaced with the properties for concrete. Table 3 summarizes the concrete material properties used in the ADINA material model.

t = varies-in (mm)	Concrete panel thickness
E_c = 4,074,281 psi (28,091.2 MPa)	Secant Modulus of Elasticity
E_{tc} = 7,129,991 psi (49,159.6 MPa)	Initial Tangent Modulus of Elasticity (Assume 1.75 x Secant Modulus)
f'_c = 5,000 psi (34.5 MPa)	Compressive strength of concrete (SIGMAC)
ε_c = 0.002	Compressive strain of concrete at SIGMAC
f'_{uc} = 4,250 psi (29.3 MPa)	Ultimate compressive strength of concrete (SIGMAU, assumed @ 85% f'_c)
ε_{uc} = 0.003	Ultimate compressive strain of concrete at SIGMAU
$f_r = 5\sqrt{f'_c}$ = 353.6 psi (2.4 MPa)	Uniaxial cut-off tensile strength of concrete
ν_c = 0.20	Poisson's Ratio
D_c = 2.172 x 10-4 lb-sec2/in4 (2,321 kg/m3)	Density
Φ_p = 0.55	Strength reduction factor for plain concrete

Table 3: Concrete material properties

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 (34.5 MPa) concrete is 353.6 psi (2.4 MPa). 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 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"[10]. ADINA uses a "smeared crack" approach to model the concrete failure. Following are summary graphic output and results for the panel under investigation.

3 ANALYSIS RESULTS

Figure 8 shows the finite element analysis (FEA) model for the panel under consideration. Positive and negative load cases as shown in Figure 7 are considered. The finite elements are arranged in a pattern that follows the fabric formwork design shown in Figure 4 and are supported with a 4-point anchor arrangement. After "form-finding", the final weight of the panel is 4,941 lbs (21,977 N). Figure 9 shows the deflected shape under the factored positive load case. The maximum service load deflection is 0.0066-in (0.168 mm).

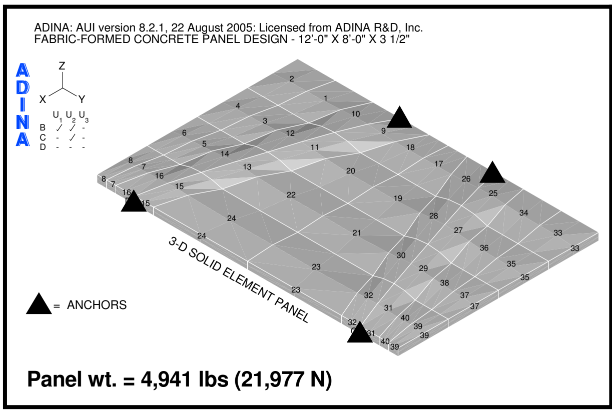


Figure 8: Panel model

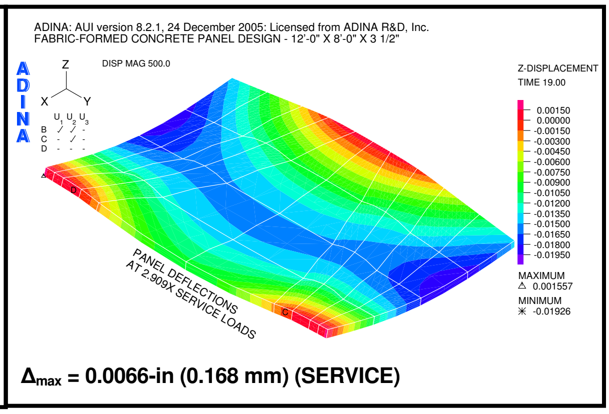


Figure 9: Panel deflections

Figures 10 and 11 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 11. 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 10 – local cracking at the supports being ignored.

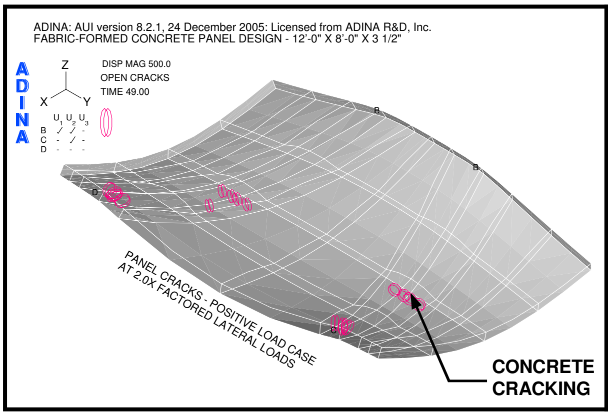


Figure 10: First panel cracks, back.

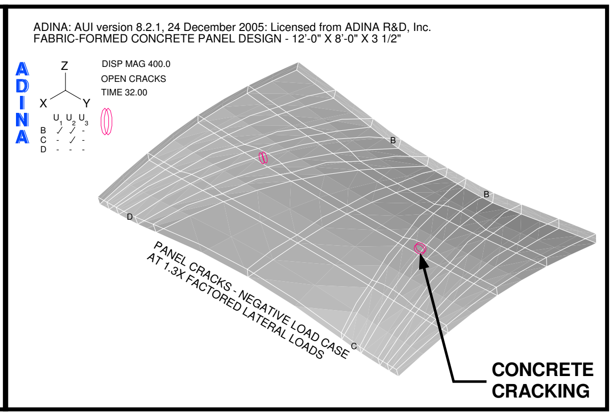


Figure 11: First panel cracks, front.

Figures 12 and 13 show tensile and compressive principal stress at a section cut along the diagonal load path. Figure 12 shows the effect of arching action similar to a strut and tie model under the positive lateral loads, a direct result of the three-dimensional funicular tension curves produced in the fabric as it deformed under the weight of the wet concrete. 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. Conversely, under the negative lateral load case the benefit is not observed, as shown in Figure 13, where the principal stresses are mostly in tension. The benefit of the funicular tension curves in the fabric formwork, which produced this panel shape, is evident. Selective reinforcement in the negative moment regions would be required if additional load capacity or a much thinner panel were desired – preference being given to noncorrosive reinforcement.

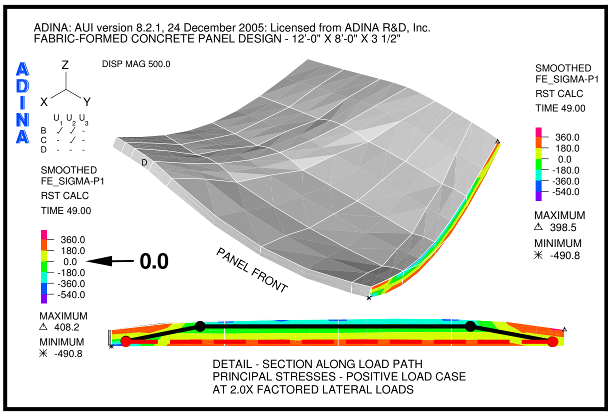


Figure 12: Principal stresses at section cut

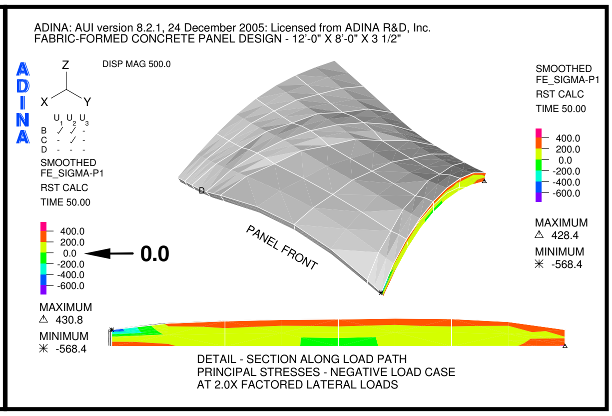


Figure 13: Principal stresses at section cut

Figure 14 shows a maximum principal tensile stress of 193 psi (1.3 MPa) for the positive lateral load case at the factored load. Figure 15 shows the maximum principal tensile stress of 289 psi (2.0 MPa) for the negative lateral load case at the factored load. The double-headed arrows indicate load paths between the supports. This corresponds to the load path for **Panel BC3** shown in Figure 3. This panel has a maximum thickness of 5.89-in (149.6 mm) and an equivalent uniform thickness of 4.26-in (108.2 mm). 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.

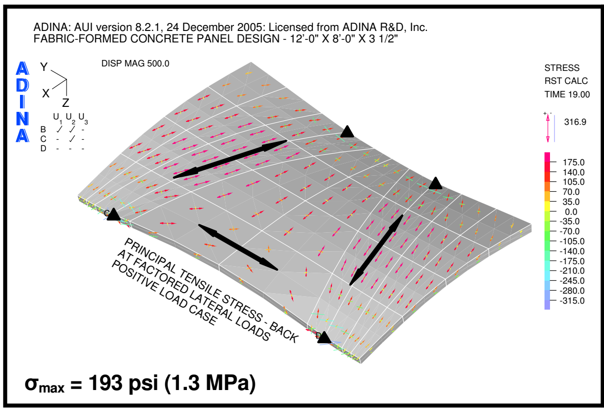


Figure 14: Panel principal stresses, back

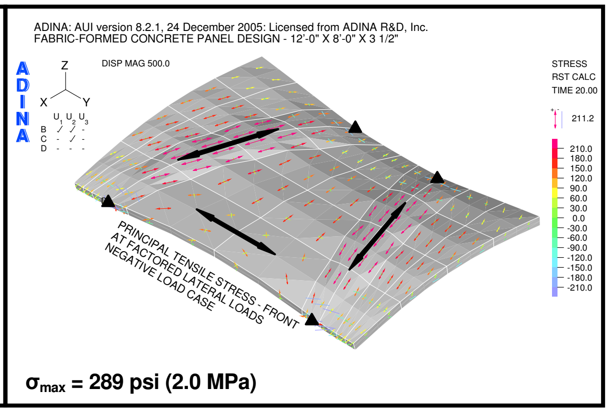


Figure 15: Panel principal stresses, front

4 CONCLUSIONS AND FURTHER RESEARCH

The procedures introduced in this paper 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 remeshing the FEA model. Key among the benefits for forming concrete using flexible fabric formworks are economies of construction, durability of the product and freedom of design expression.

Much work remains to be done including design and modeling verification, investigation of reinforcement types and options, development of new types of formwork fabrics and the development of standards and guidelines for this unique means of forming concrete members.

REFERENCES

[1] ACI Committee 347, *Guide to Formwork for Concrete* (ACI 347-04). Farmington Hills, Michigan: American Concrete Institute (2004).
[2] ACI Committee 334, *Construction of Concrete Shells Using Inflated Forms* (ACI 334.3R-05). Farmington Hills, Michigan: American Concrete Institute (2005).
[3] W. Neff, *United States Patent* No. 2,270,229 (1942).
[4] M. West, *Fabric-Formed Concrete Members*, Concrete International, Vol. 25(10), pp. 55+ (October 2003).
[5] M. West, *Fabric-Cast Concrete Wall Panels*, Materials Technology Workshop, Department of Architecture, University of Manitoba, Canada. [Internet, WWW]. Address: http://www.umanitoba.ca/cast_building/resources.html (April 2003).
[6] M. West, *Prestressed Fabric Formwork for Precast Concrete Panels*, Concrete International Vol. 26(4), pp. 60+ (April 2004).
[7] R. Schmitz, *Fabric-Formed Concrete Panel Design*, Master's thesis, Milwaukee School of Engineering, Milwaukee, Wisconsin 53202 (2004).
[8] R. Schmitz, *Fabric-Formed Concrete Panel Design*, Proceedings of the 17th Analysis and Computation Specialty Conference on the 2006 Structures Congress CDROM published by ASCE, ISBN 0-7844-0878-5 (2006).
[9] ADINA R&D, Inc., *ADINA* (Version 8.6), [Computer program], Available: ADINA R&D, Inc., 71 Elton Avenue, Watertown, Massachusetts 02472 (May 2009).
[10] ADINA R&D, Inc., *ADINA – Theory and Modeling Guide - Volume 1: ADINA*, Report ARD 09-7, Watertown, Massachusetts: ADINA R&D, Inc. (May 2009).
[11] 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, pp. 1-10 (2001).
[12] T. Baker, *Amoco 2006 Stress-Strain*, Atlanta, Georgia: Amoco Fabrics and Fibers Company, [Internet, e-mail to the author] (2002).
[13] K.L. Soderman and J.P. Giroud, *Relationships Between Uniaxial and Biaxial Stresses and Strains in Geosynthetics,* Geosynthetics International Vol. 2(2), pp. 495-504 (1995).
[14] Terram Ltd., *Designing for Soil Reinforcement (Steep Slopes)*, Handbook, (United Kingdom: Terram Ltd.), pp. 19-22. [Internet, WWW]. Address: http://www.terram.com (May 2000).
[15] T. Baker, Amoco 2006 Relaxation Results, Atlanta, Georgia: Amoco Fabrics and Fibers Company, [Internet, e-mail to the author] (2005).
[16] ACI Committee 318, *Building Code Requirements for Structural Concrete* (ACI 318-02) *and Commentary* (ACI 318R-02), Farmington Hills, Michigan: American Concrete Institute, (2002).