# Fabric-formed concrete member design:

## A procedure to predict the contour of a fabric cast panel

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## A procedure to predict the contour of a fabric cast panel

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## Abstract

Concrete members have traditionally been cast using a rigid formwork. Recently, however, the American Concrete Institute's Committee 334 [2] has introduced a guide for the construction of shells using inflated forms. Straightforward methods of analysis and design are available for the traditionally cast prismatic concrete member – be it a concrete floor, beam, wall or column member. This is not the case for the concrete member cast in a flexible fabric formwork. The final member form, performance and function of the fabric membrane and the reinforcement of the member for design loads all add to the complexities of the member's analysis and design. To date, no design procedures or method to predict the deflected shape of a fabric cast concrete member have been developed.

While posited 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 this unique method of forming concrete into everyday practical use by the construction industry.

Analytical modeling and design techniques presented in this paper will offer the design community, architects and engineers, 1) an alternative method for expressing themselves using flexible fabric formwork 2) the ability to optimize concrete members and 3) realize economies of construction leading to a conservation of construction materials and a greener more *sustainable* planet.

**Keywords**: Form-finding, optimization, flexible formworks, sustainable design, concrete member design.

## 1. Introduction

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.

Historically both civil engineering and architectural projects have benefited by the use of fabric as a formwork for concrete containment. This versatile means of containing concrete saw some of its first use in civil engineering works such as erosion control. Developed and patented by Construction Techniques, Inc. in the mid-1960's Fabriform® is the original fabric-formed concrete system. Their products include Articulated Block, Filterpoint, Unimat, Concrete Bags and Pile Jackets. Engineers who have reported on the use of fabric-formed concrete lining used for slope protection include Phildysh & Wilson [10] and Lamberton [8]. 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, Schmitz [13].

Given the need for a mortar or concrete to set and cure properly the use of a flexible formwork might appear to be counterintuitive for casting any concrete member yet casting concrete into flexible formworks may in fact be used nearly anywhere a rigid formwork is used.

The American Concrete Institute's Committee 347 [3] formally introduced the first standard guide for the design and construction of formwork in 1963. Even though several methods of construction using inflated forms have been available since the early 1940's, Neff [9], a standard guide by ACI Committee 334 first became available in 2005. It can take many years to standardize methods of construction today regarded as experimental.

### 1.1 Research efforts

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. For more than a decade Professor Mark West, Director of the Centre for Architectural Structures and Technology (C.A.S.T.) at the University of Manitoba, Canada, and his architectural students have been exploring the use of flexible formwork for casting concrete wall panels and other members, West [14, 15, 16]. Other countries where researchers are investigating this unique method of forming concrete include Belgium, Chile, Demark, England the Netherlands, Scotland, Switzerland and the United States.

## 2. Analysis methodology

Straightforward methods of analysis and design are available for the traditionally cast concrete member – be it a concrete floor, beam, wall or column member. However, due to the complex configuration of fabric-formed concrete members, an analytical method of analysis utilizing finite element software (FEA) is required.

### 2.1 A design procedure

A four-step procedure for analytically modeling the fabric formwork, loaded with the plastic concrete, was developed in order to determine the shape a concrete wall panel might take and analyze it. This procedure, first developed in the author's graduate Capstone Project, Schmitz [11], and refined in a 2006 paper, Schmitz [12], allows one to design a fabric cast concrete panel. These steps are:

1. Determine primary load paths to panel anchor points due to lateral and gravity loads.
    a. Use a series of 3-D Solid element panels with various boundary conditions.

   b. Examine the panels and determine the direction the maximum principal stresses take. (These are the "load paths".)

2. Use Solid finite elements to model the fabric and plastic concrete material. These elements are arranged to define the panel's lines of support.
3. "Form-find" the shape of the panel by incrementally increasing the thickness of the Solid elements used to model the plastic concrete until equilibrium in the supporting fabric formwork's Solid elements has been reached. 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 being imposed upon it.

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. By utilizing this iterative process, obtaining an optimal panel shape is possible.

### 2.2. Finite element analysis (FEA) model development

Model development and analysis of the fabric cast concrete panel is performed utilizing the structural analysis/finite element program ADINA [4, 5]. Efficient modeling played an essential role in the formation 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 and gravity loads under the given set of boundary conditions. While a surface load defined by a "quadratic surface spatial function", representing the weight of the concrete could be used to find the shape of the panel using the same iterative procedure, it would not be as efficient as the proposed method – and defining element nodal locations would be both difficult and time consuming.

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.

### 2.3 Fabric model elements and material properties

The ADINA 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 modulus of elasticity, $E_a$, being taken. Thus, the modulus of elasticity is approximately equal in each direction.

Stress strain and relaxation data for the Amoco 2006 geotextile fabric, the material being modeled, was obtained from Amoco Fabrics and Fibers Company, Baker [6, 7]. Table 1 summarizes the properties for this *elastic-orthotropic* material.

| | |
|---|---|
| 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

### 2.4 Slurry model elements and material properties

The ADINA computer model representing the slurry material uses 27-node, 3-D Solid elements. 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 x 10-4 lb sec2/in4 (2,321 kg/m3) | Density |

Table 2: Slurry material properties

A summary of our design procedure is shown graphically in Figures 1-4.

## 3. Panel optimization 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

After "form-finding" our panel is as shown in Figure 5 it may now be analyzed for strength under lateral and gravity self-weight loads after discarding the fabric elements, replacing the slurry material properties with concrete material properties, Table 3, and using the 4-point anchor arrangement **BC3** shown in Figures 1 and 6. Two lateral load cases are considered, a positive load case and a negative load case as shown in Figure 4. 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.

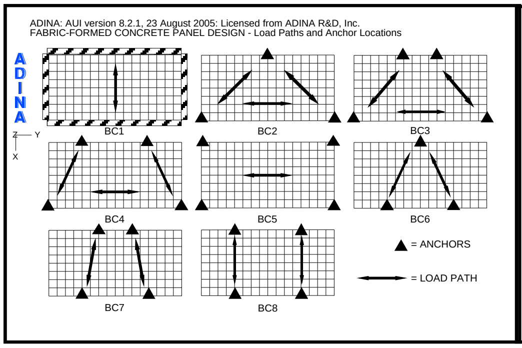

Figure 1: Step 1– Load path study

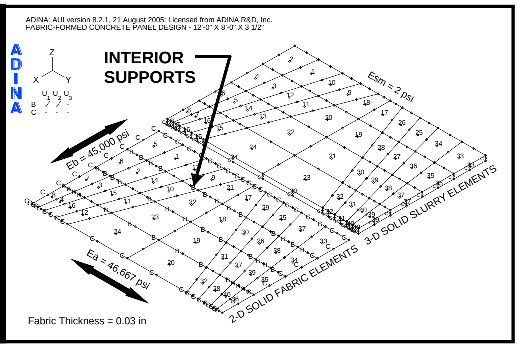

Figure 2: Step 2 – Combined fabric and slurry model (1-in = 25.4 mm, 1 psi = 6.9 kPa)

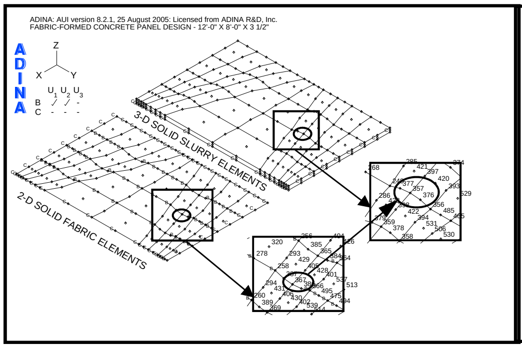

Figure 3: Step 3– “Form-finding” models

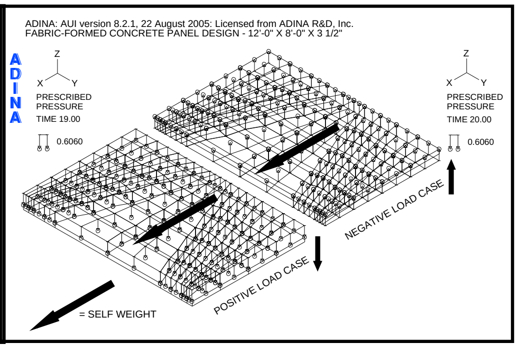

Figure 4: Step 4 – Analyze and design panel

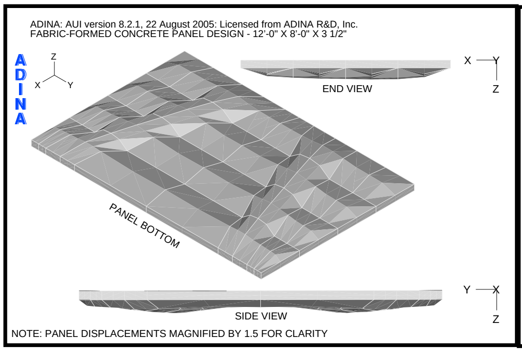

Figure 5: Panel shape after “form-finding”

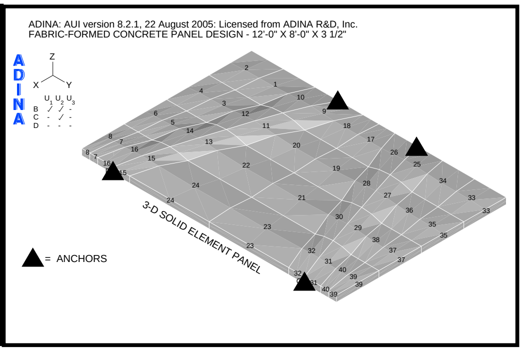

Figure 6: Design panel with anchor locations

| | |
|---|---|
| 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) |
| $\varepsilon_c$ = 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) |
| $\varepsilon_{uc}$ = 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 |
| $\nu_c$ = 0.20 | Poisson's Ratio |
| $D_c$ = 2.172 x 10-4 lb sec$^2$/in$^4$ (2,321 kg/m$^3$) | Density |
| $\Phi_p$ = 0.55 (= 0.60 in ACI 318-14) | Strength reduction factor for plain concrete |

Table 3: Concrete material properties

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 was 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). The panel was analyzed using the strength design method for plain concrete and ACI 318-02, Section 22 [1]. Details of these results may be found in the previously published paper referenced above, Schmitz [12].

The most significant finding of these analyses were the loading conditions under which the panel first cracked. For case two, the negative load case, the first cracks occur at 1.3-times the factored load and for case one, the positive load case, the panel did not crack, within the body of the panel, until 2 times the factored positive load was reached – local cracking at the supports being ignored.

The beneficial effect of the funicular tension curves formed in the fabric, which produced this panel shape, is evident. Figures 7 and 8 show tensile and compressive principal stresses at a section cut along the diagonal load path. Figure 7 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 was not observed, as shown in Figure 8, where the principal stresses are mostly in tension. 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. Alternatively, two panels linked back-to-back might naturally provide the needed lateral strength without a great deal of additional reinforcement and provide a decorative finish inside and out. Where desired, insulation between the panels could be added creating a sandwich panel.

So while using geotextile fabric as a formwork has a number of advantages including:

- Forming very complex shapes are possible.
- It is strong, lightweight, inexpensive and reusable.
- Less concrete and reinforcing are required leading to a conservation of materials.

- Filtering action improves the surface finish and durability of the member.

It also has several disadvantages including:

- Relaxation can occur due to prestress forces in the membrane.
- There is the potential for creep in the geotextile material due to hydration of the concrete mix.
- The concrete must be placed carefully and the fabric formwork not jostled while the concrete is in a plastic state.

Until new fabrics are developed however, the benefits of using geotextiles far outweighs any disadvantages.

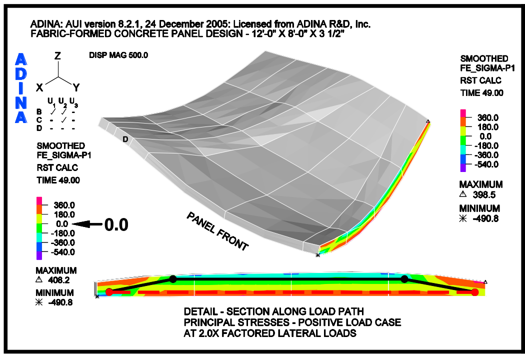

Figure 7: Principal stresses at section cut

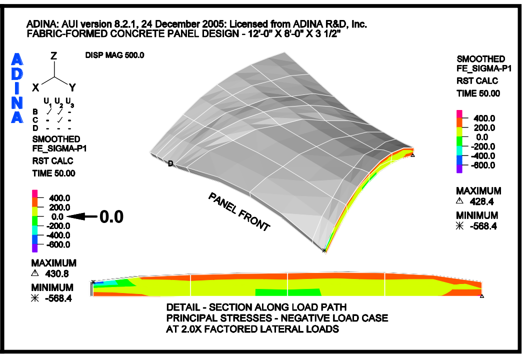

Figure 8: Principal stresses at section cut

## 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 members 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, "proof of concept", 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.

## Acknowledgement

I would like to acknowledge the efforts of Professor Mark West, Director of C.A.S.T. at the University of Manitoba, and his students whose work on fabric and flexible formworks continues to be an inspiration for me and my research of this unique way of forming concrete members.

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