FABRIC-FORMED CONCRETE MEMBER DESIGN

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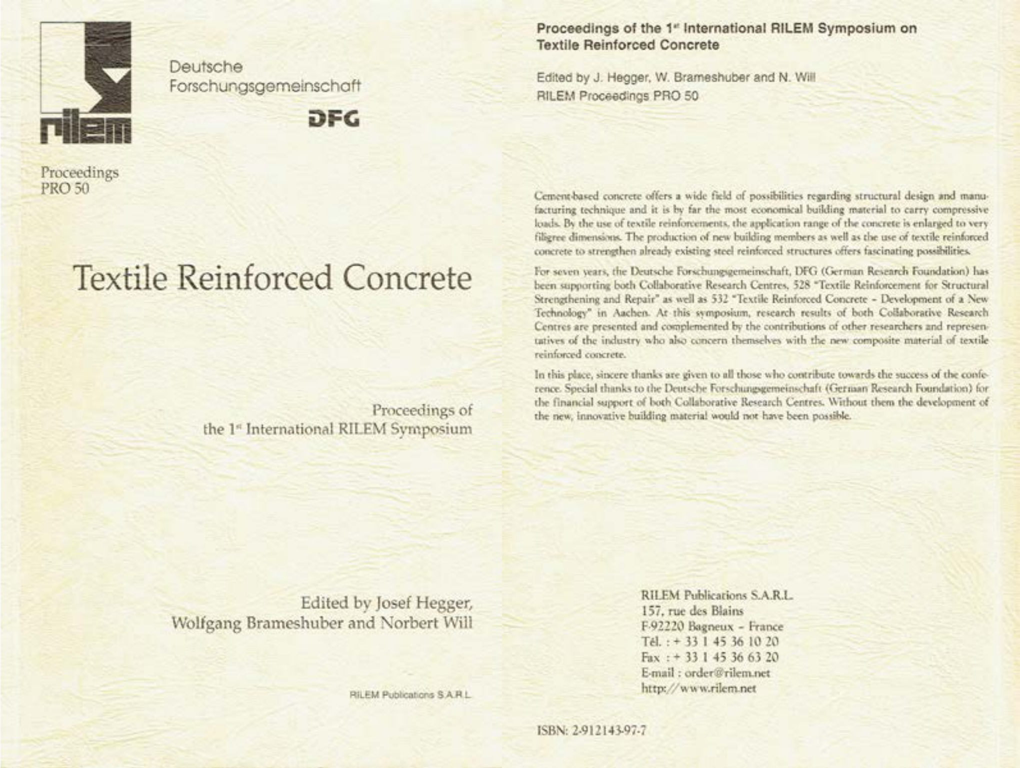

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Textile Reinforced Concrete

Proceedings of
the 1st International RILEM Symposium

Edited by Josef Hegger,
Wolfgang Brameshuber and Norbert Will

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Proceedings of the 1st International RILEM Symposium on Textile Reinforced Concrete

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Cement-based concrete offers a wide field of possibilities regarding structural design and manufacturing technique and it is by far the most economical building material to carry compressive loads. By the use of textile reinforcements, the application range of the concrete is enlarged to very filigree dimensions. The production of new building members as well as the use of textile reinforced concrete to strengthen already existing steel reinforced structures offers fascinating possibilities.

For seven years, the Deutsche Forschungsgemeinschaft, DFG (German Research Foundation) has been supporting both Collaborative Research Centres, 528 "Textile Reinforcement for Structural Strengthening and Repair" as well as 532 "Textile Reinforced Concrete – Development of a New Technology" in Aachen. At this symposium, research results of both Collaborative Research Centres are presented and complemented by the contributions of other researchers and representatives of the industry who also concern themselves with the new composite material of textile reinforced concrete.

In this place, sincere thanks are given to all those who contribute towards the success of the conference. Special thanks to the Deutsche Forschungsgemeinschaft (German Research Foundation) for the financial support of both Collaborative Research Centres. Without them the development of the new, innovative building material would not have been possible.

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ABSTRACT: Concrete members have traditionally been cast using a rigid formwork. 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 paper introduces a design procedure that allows one to design a fabric cast concrete wall panel.

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. 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.

Analytical modeling and design techniques presented in this paper will allow members of the design community another way to express themselves using a flexible fabric formwork.

1 INTRODUCTION

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 [Wes03]. 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 [Wes02, Wes04].

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.

For demonstration purposes, a 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).

1.1 Proposed design procedure

This paper presents a four-step procedure developed in the author's graduate Capstone Project that allows one to design a fabric cast concrete panel [Sch04]. These steps are:

1. Determine the paths the lateral loads take to the points where the wall panel is to be anchored.
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.
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. 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 utilizing the above four-step procedure, it is expected that obtaining an optimal panel shape is possible. 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. The procedure becomes an iterative process.

2 ANALYSIS METHODOLOGY AND MATERIALS

Model development and analysis of the fabric cast concrete panel is performed utilizing the structural analysis/finite element program ADINA [ADI04, ADI04a]. 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.

2.1 Fabric model material properties

The 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). 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 [AST01].

Stress-strain data for the Amoco 2006 geotextile fabric obtained from Amoco Fabrics and Fibers Company allowed the properties shown in Table 2.1 for this elastic-orthotropic material to be entered into the ADINA material model [Bak02]. 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 [Sod95].

Table 2.1. AMOCO 2006 geotextile fabric material properties

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

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 [Ter00]. 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 [Bak05].

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 2.2 summarizes the slurry material properties used in the ADINA material model.

Table 2.2. Slurry material properties

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

2.3 Step 1 – Determination of load paths

In the first step, a 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 an examination of the principal stresses is made. For this study, any uniform material type may

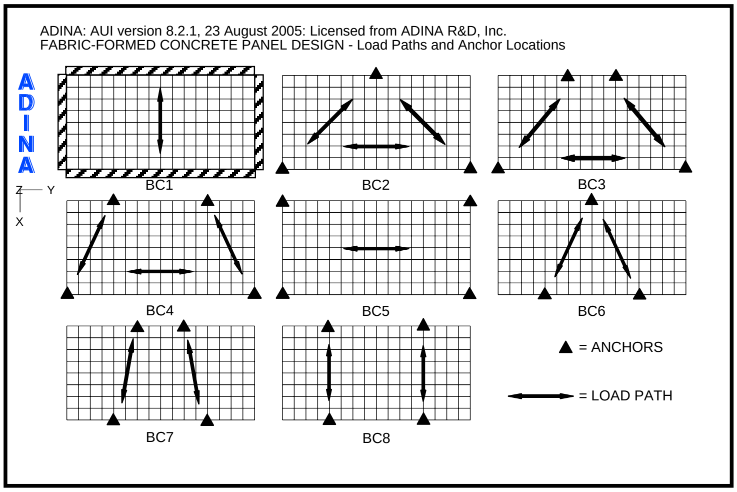

Figure 2.1. Panel load paths and anchor locations.

be used. Figure 2.1 shows the results of these panel investigations for a variety of boundary conditions. The general direction the maximum principal stresses take is indicated by the double-headed arrows.

Note in Figure 2.1 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 demonstration 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 2.1, the formwork is laid out and the interior and perimeter boundary conditions are introduced as shown in Figure 2.2. Interior supports are indicated by a **"B"** in this figure.

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.

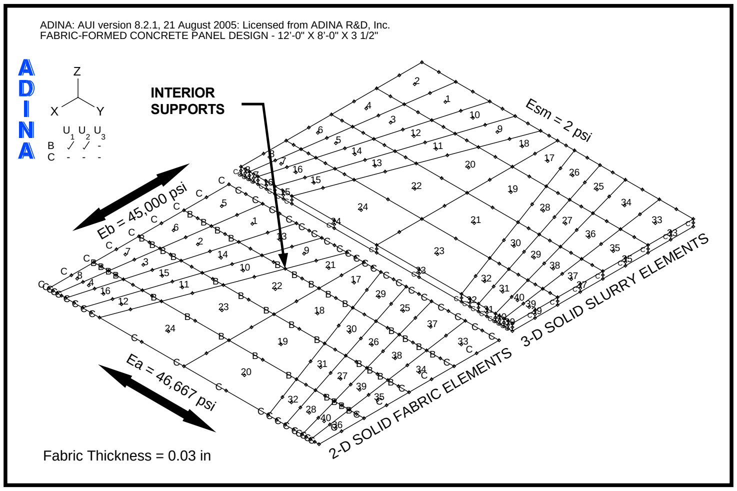

Figure 2.2. Combined fabric and slurry model. (1-in = 25.4 mm, 1 psi = 6.9 kPa)

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 2.2. 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 2.3) by the amount the fabric displaces (e.g., at node 367, Figure 2.3). 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%.

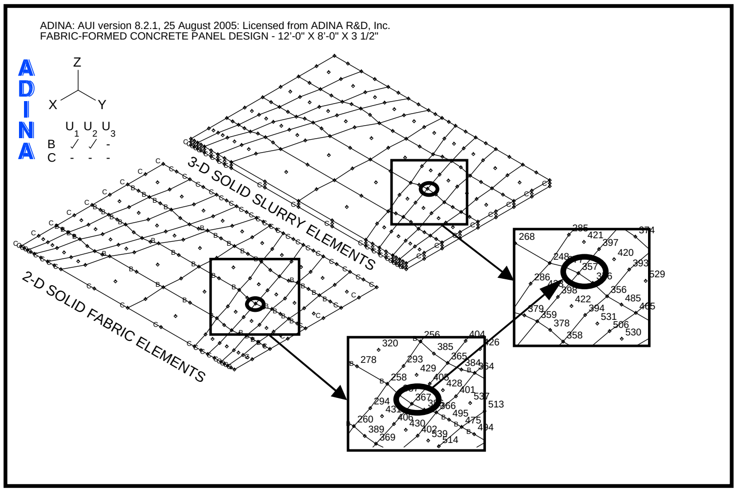

Figure 2.3. Combined fabric and slurry model.

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 2.4 shows the results of “form-finding” the panel shape made up of the slurry material. The boundary conditions that created it are illustrated in Figure 2.2.

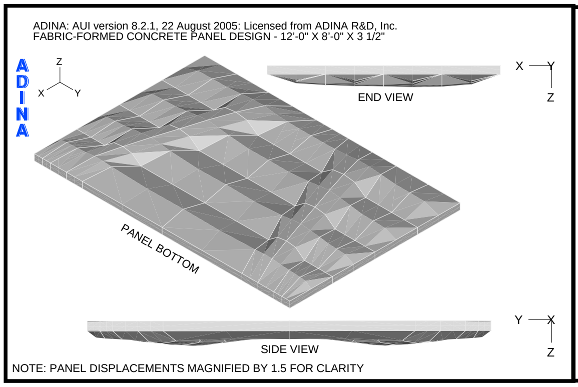

Figure 2.4. Panel shape after “form-finding”.

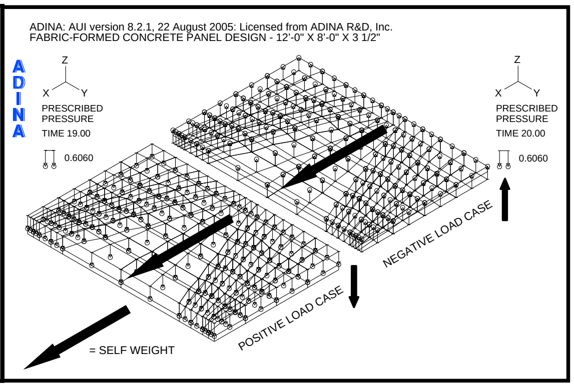

Figure 2.5. Panel load cases. (1 psi = 6.9 kPa)

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

The panel shape defined in Figure 2.4 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 2.5. 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 [ACI02].

The properties for the slurry material are now replaced with the properties for concrete. Table 2.3 summarizes the concrete material properties used in the ADINA material model.

Table 2.3. Concrete material properties

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
$D_c = 2.172 \times 10^{-4}$ lb-sec^2/in^4 (2,321 kg/m^3)	Density
$\Phi_p = 0.55$	Strength reduction factor for plain concrete

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" [ADI04a]. ADINA uses a "smeared crack" approach to model the concrete failure. Following are summary graphic output and results for the panel under investigation.

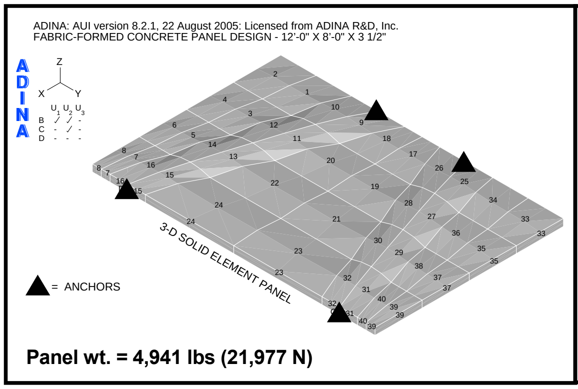

Figure 3.1. Panel model.

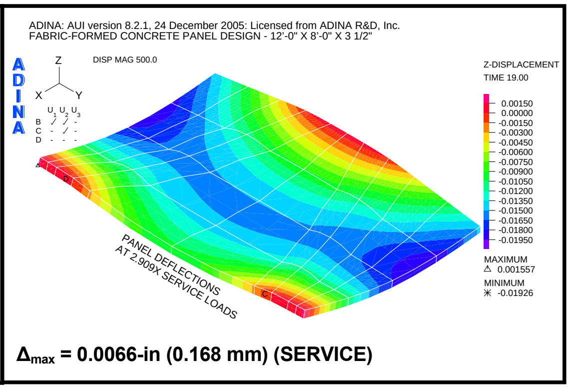

Figure 3.2. Panel deflections.

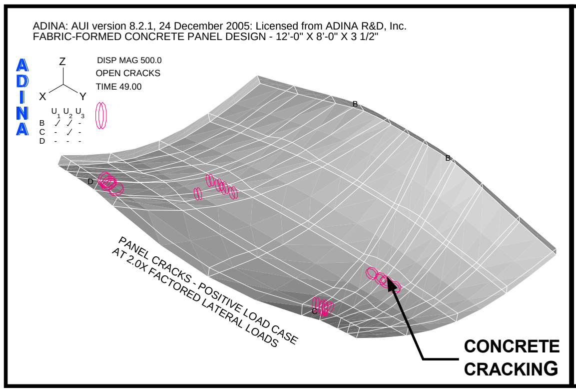

Figure 3.3. First panel cracks, back.

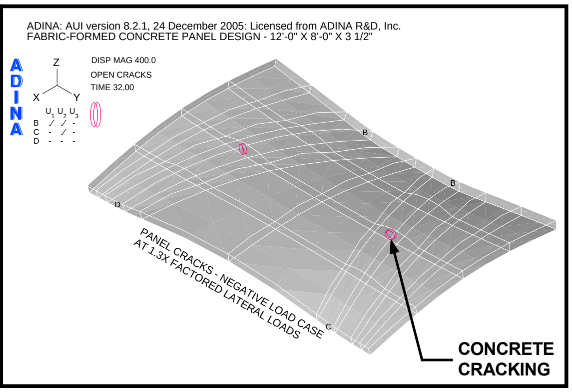

Figure 3.4. First panel cracks, front.

3 ANALYSIS RESULTS

Figure 3.1 shows the finite element analysis (FEA) model for the panel under consideration. Positive and negative load cases as shown in Figure 2.5 are considered. The finite elements are arranged in a pattern that follows the fabric formwork design shown in Figure 2.2 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 3.2 shows the deflected shape under the factored positive load case. The maximum service load deflection is 0.0066-in (0.168 mm).

Figures 3.3 and 3.4 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 3.4. 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 3.3 – local cracking at the supports being ignored.

Figures 3.5 and 3.6 show tensile and compressive principal stress at a section cut along the diagonal load path. Figure 3.5 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. Conversely, under the negative lateral load case the benefit

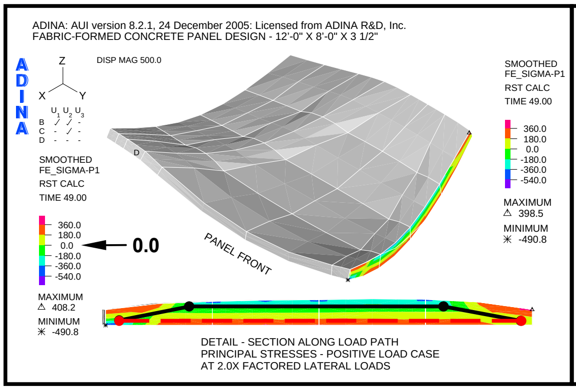

Figure 3.5. Principal stresses at section cut.

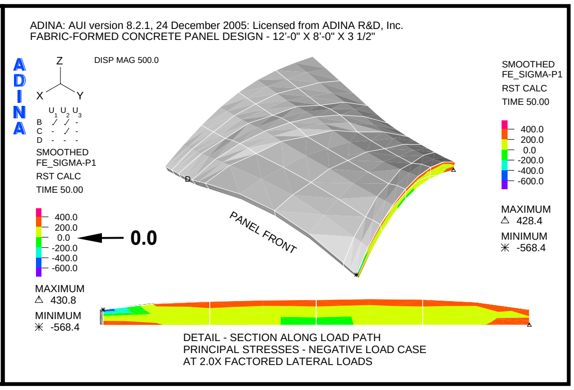

Figure 3.6. Principal stresses at section cut.

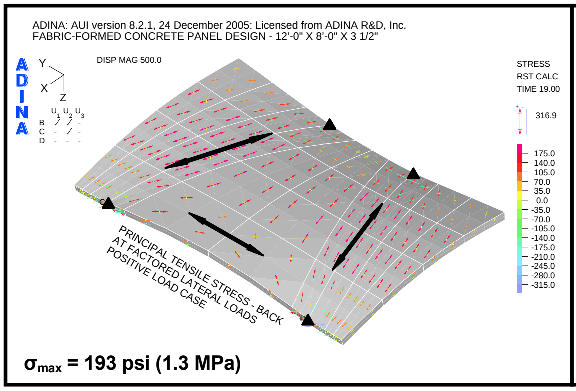

Figure 3.7. Panel principal stresses, back.

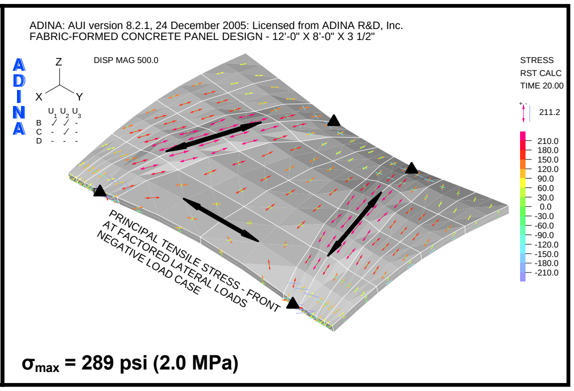

Figure 3.8. Panel principal stresses, front.

is not observed, as shown in Figure 3.6, 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.

Figure 3.7 shows a maximum principal tensile stress of 193 psi (1.3 MPa) for the positive lateral load case at the factored load. Figure 3.8 shows the maximum principal tensile stress of 289 psi (2.0 MPa) for the negative 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 2.1. 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.

4 CONCLUSIONS

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. 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.

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