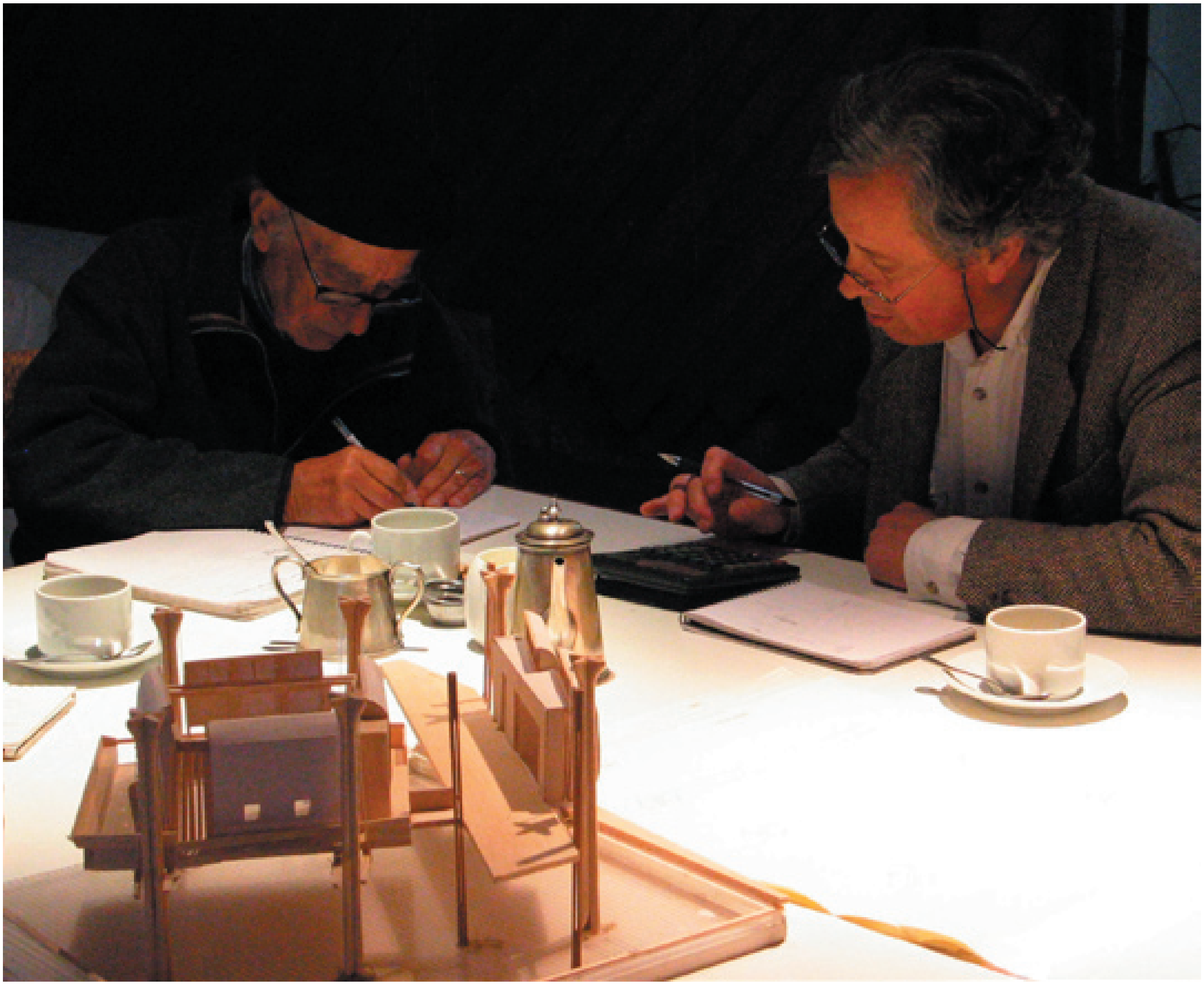
THIN-SHELL CONCRETE   FROM FABRIC MOLDS

technologies and instigations from
La Ciucad Abierta (the “Open City) Projecto Taller de Obras

by Mark West



INTRODUCTION

This article describes methods of forming prefabricated, fiber-reinforced, thin-shell concrete structures using molds made from hanging flat sheets of fabric. These fabric sheets are allowed to deflect into naturally occurring funicular geometries, producing molds for lightweight funicular compression vaults and double curvature wall panels.

These methods were developed to provide lightweight wall and floor structures for the *Taller de Obras* project, a new architectural atelier building at the Open City in Ritoque Chile, designed by architects Miguel Equem and David Jolly (seen above with a preliminary model of the building), in collaboration with the Centre for Architectural Structures and Technology (C.A.S.T.) Laboratory at the University of Manitoba's Faculty of Architecture.

This document is presented in Three parts: 1: C.A.S.T.'s proposals for the floor structure construction, including a brief overview of some of the architectural possibilities opened up by the ability to fabricate pre-cast funicular thin-shell vaults from fabric-formed molds; 2: a description of a method for fabricating double curvature thin-shell wall panels from hanging sheets of fabric; and 3: a gallery of photographs exploring some of the new architectural possibilities opened up by the research done for this project.

PART 1:

COMPRESSION VAULT FLOOR SLAB USING PRE-CAST THIN-SHELL PAN FORMWORK PRODUCED FROM FABRIC-FORMED MOLDS

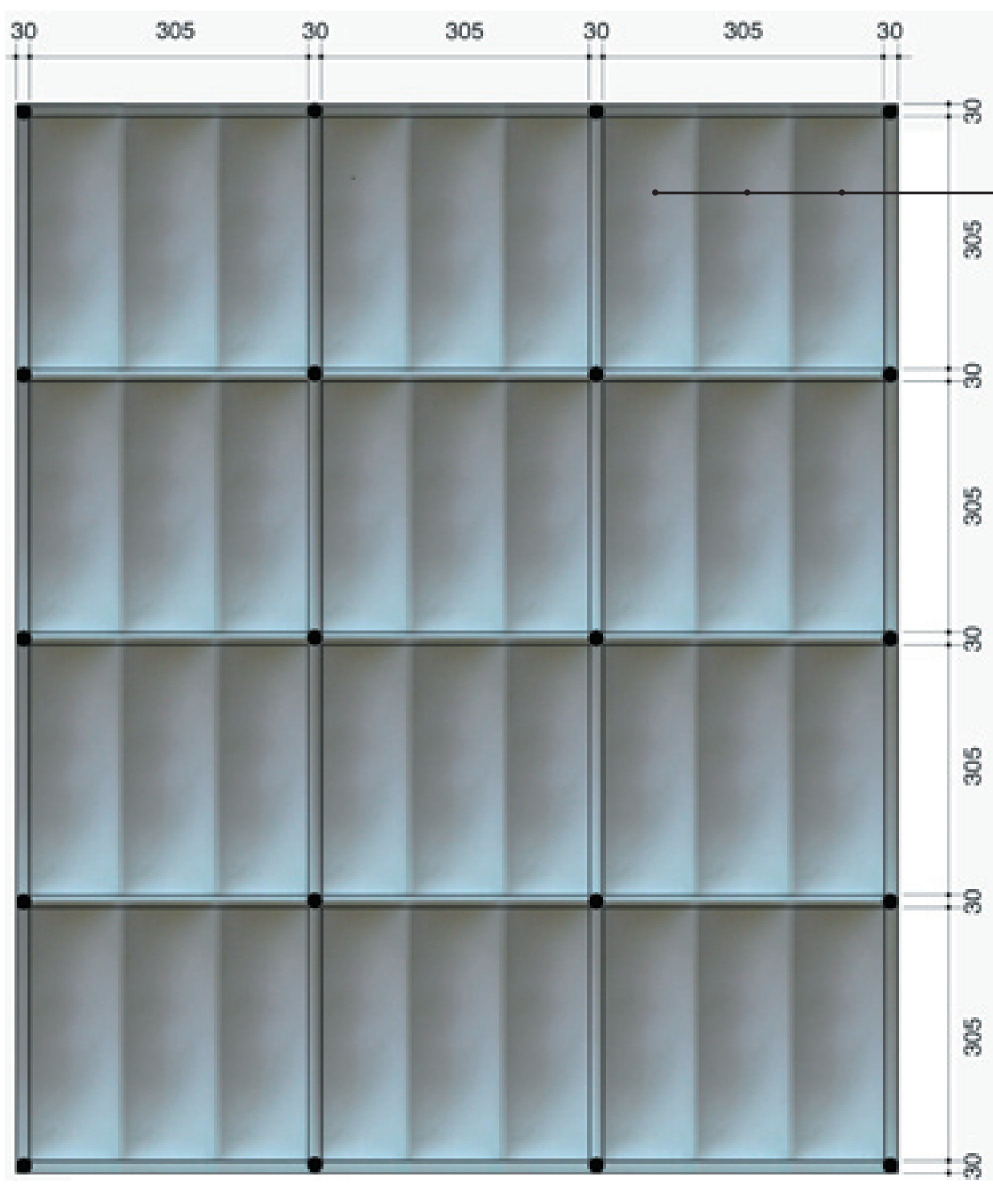
The Taller de Obras floor structure is a cast-in-place reinforced concrete slab supported by a 3 m by 3 m grid of supporting beams (plan below). This project proposes to reduce the amount of reinforcing steel this slab requires by using pre-cast thin-shell funicular vaults (approximately 3 m by 1 m), made from fiber-reinforced concrete to serve as stay-in-place formwork pans for a cast-in-place floor slab designed to span by compression between its integrally formed beams.

The production method for these pan formwork vaults is illustrated in the pages below

Cast-in-place concrete

Reinforcing steel in integral valley beams

Prefabricated, fiber-reinforced thin-shell compression vault formwork pans.



Floor structure viewed from below showing the pattern of individual precast compression vault formwork pans for a cast-in-place slab.

FIRST TEST OF FABRIC FORMED MOLD FOR PRODUCTION OF PRECAST THIN-SHELL FUNICULAR VAULTS

Lafarge Precast Factory, Winnipeg, Canada -- April 2004

1. A flat rectangular sheet of geotextile fabric is hung from a steel frame

2. A uniform thickness of Glass fiber Reinforced Concrete (GFRC) is applied to the hanging fabric.

3. The resulting funicular shell is inverted to make a mold for precast production.

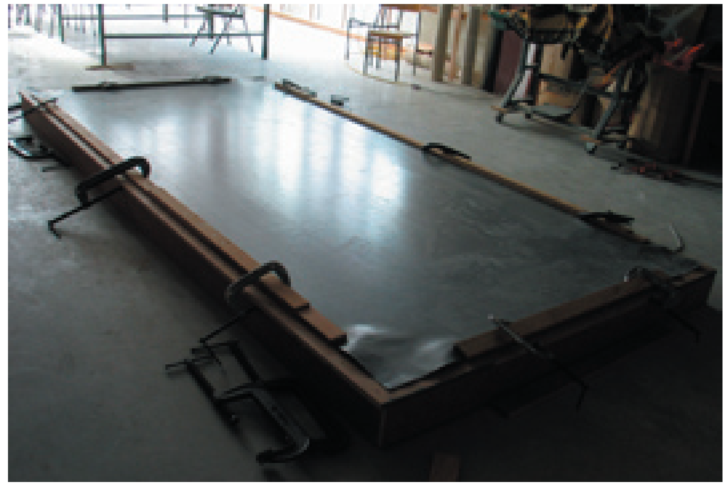
4. A thin-shell GFRC vault is produced from the fabric-formed mold.

5. Plaster model of a precast funicular vault structure (supported here by fabric-formed prestressed plaster trusses). C.A.S.T. Laboratory 2007

SECOND TEST OF FABRIC FORMED MOLD FOR PRODUCTION OF PRECAST THIN-SHELL FUNICULAR VAULTS

Lafarge Precast Factory, Winnipeg, Canada -- April 2007

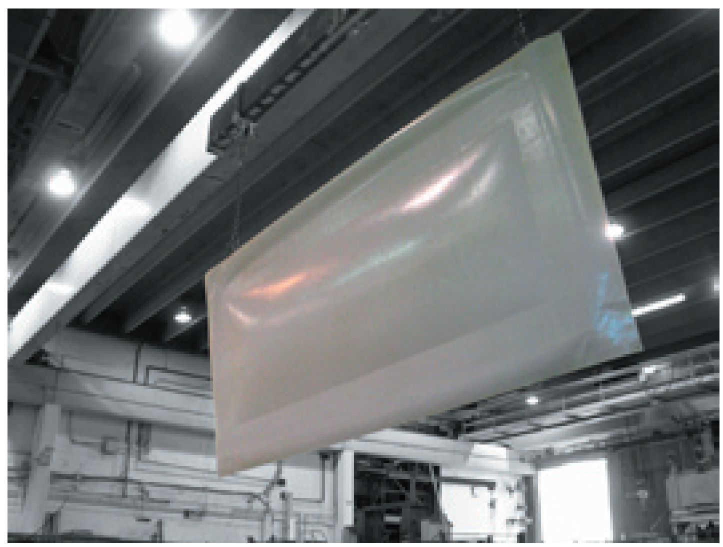
1. A simple open frame is constructed. We used 3/4 in (19 mm) plywood, built to the full-scale dimensions of the proposed Taller de Obras formwork pans (1m x 3m opening).



2. A coated woven polyethylene fabric is stapled to 3/4 in. (19 mm) plywood strips and stretched over the opening to remove any wrinkles that might form in the sheet.

3. The wood strips are screwed to the frame, thus fixing the fabric in place. A uniform thickness of fiber-reinforced concrete is placed over the fabric. In this case a sprayed shotcrete is used, but hand application of the concrete is also possible. The edges are reinforced with steel rebar.

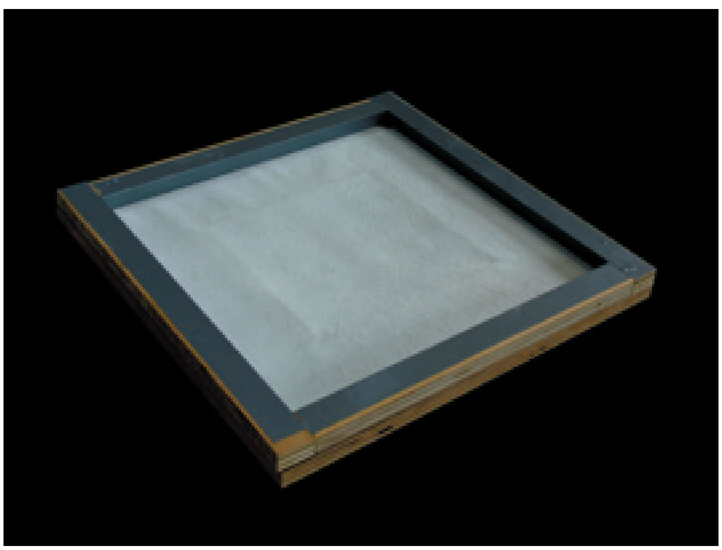
Woven high density polyethylene or polypropylene fabrics can be manufactured with a smooth waterproof coating on one side, and a fuzzy non-woven fabric welded to the other. If the concrete is applied to the non-woven side, the fabric will permanently adhere to it, providing a smooth, permanent, plastic-coated release surface for the mold.

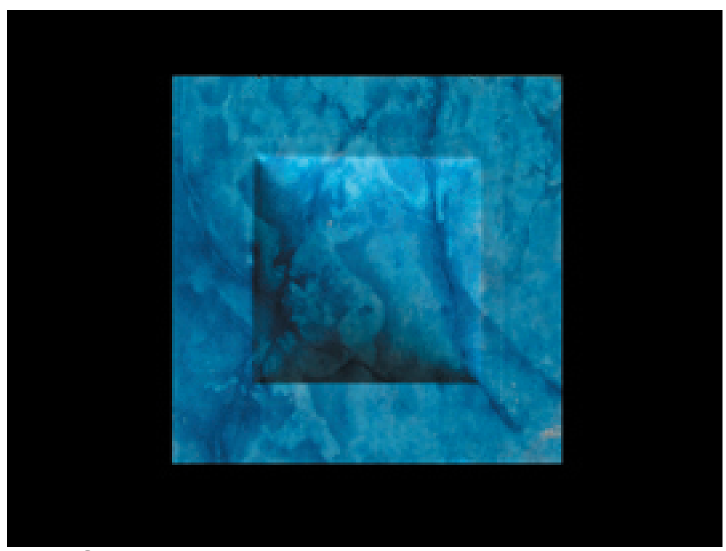


4. The funicular shell thus formed is removed from the frame to be used as a plastic-coated mold for precast production of fiber-reinforced thin-shell funicular compression vaults. These vaults can be used directly as structure, or as stay-in-place formwork pans.

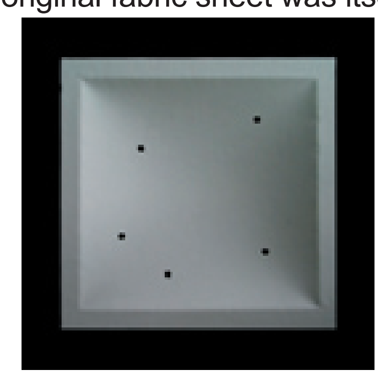
OTHER APPLICATIONS OF FABRIC-FORMED PRECAST COMPRESSION VAULTS

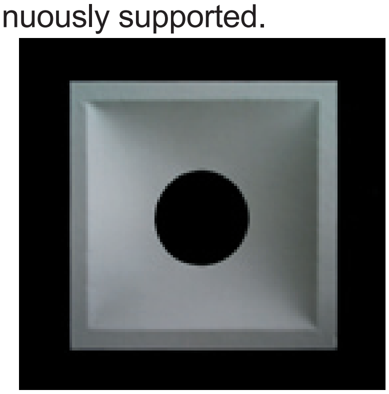
Scaled physical models are excellent tools for developing and predicting practical techniques for full-scale fabric formwork construction. Based on 15 years of research experience, we have found that whatever we can build in scaled working models can be constructed at full-scale. The scaled compression shell molds shown below illustrate a small sample of the vault forms that can be constructed using flat sheets of fabric.

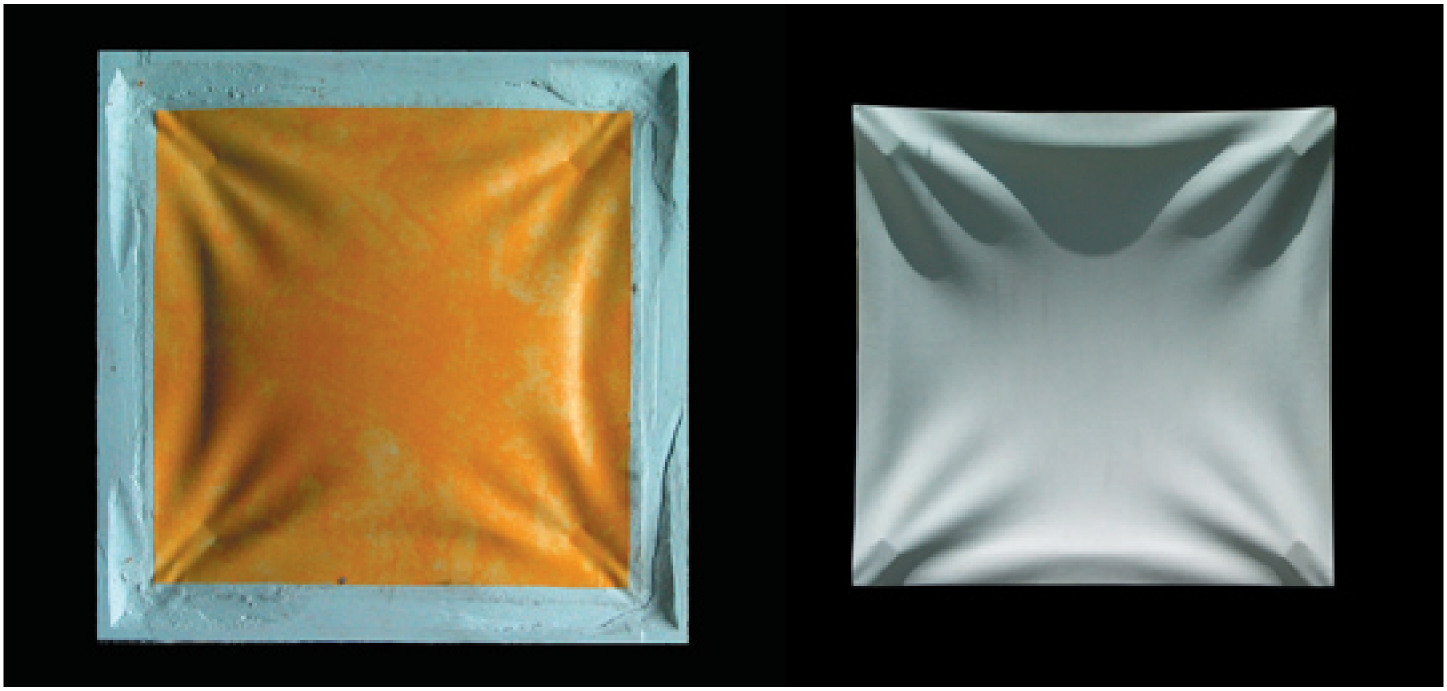




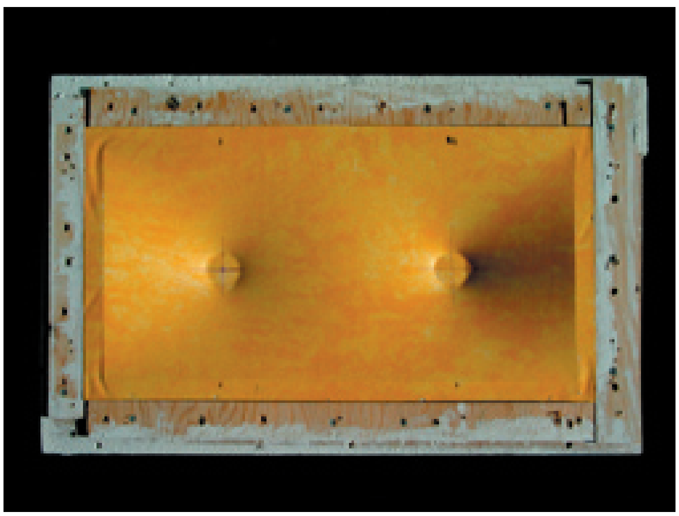
Closely following the methods developed for the Taller de Obras project, this model used a plastic-coated fabric sheet placed over a square opening (above left) to make a plastic-coated mold (above right). Three of the funicular compression vaults cast from this mold are shown below. These vaults require continuous support along all four edges because the original fabric sheet was itself continuously supported.





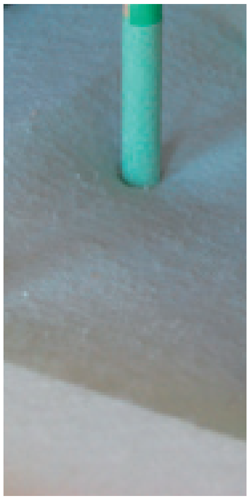
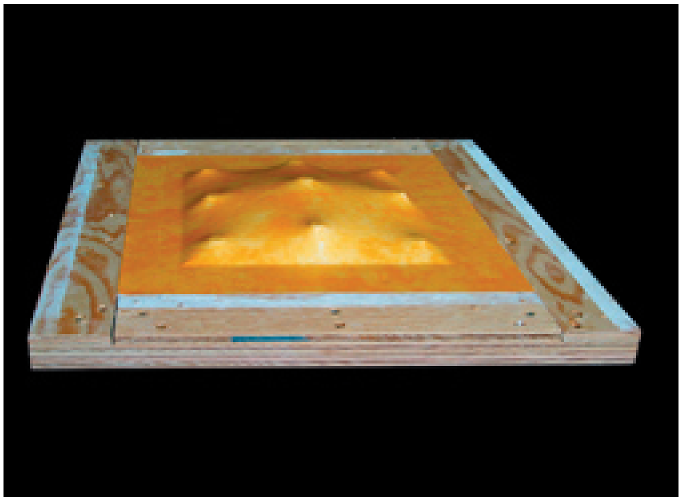
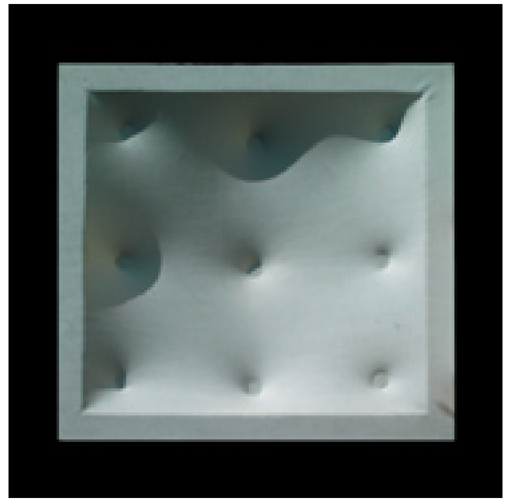


This mold (above left) was made by supporting a flat sheet of fabric from its four corners. The funicular shell cast from this mold (above right) resolves its compression forces to four point support at the corners. Horizontal thrust forces can be contained by tension reinforcing integrated into the shell along its perimeter, connecting the four support points in a tension ‘ring’.



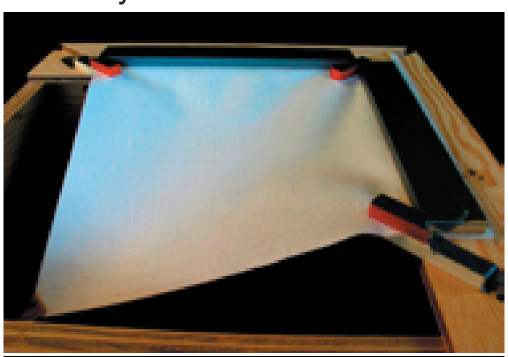
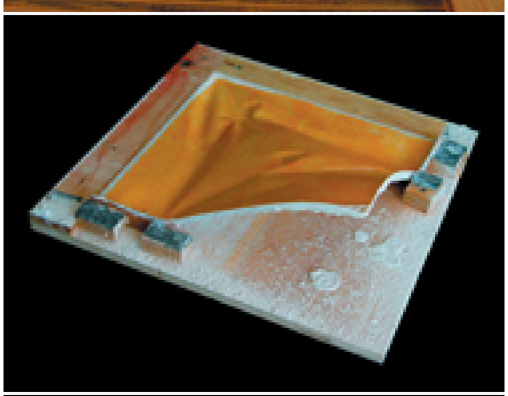
The mold (above left) was formed by a rectangular sheet of fabric that was pre-tensioned by pushing upwards at two points (above right). The shells produced from this mold (at left) are cantilevered shells -- their lower surface is in compression and their upper surface is reinforced for tension.

It will be appreciated that a multitude of funicular vault forms can be produced by supporting a flat fabric sheet in different ways. The tension geometries assumed by the fabric under load will produce molds for funicular compression shells shaped to support the same (but reversed) loading patterns.

A mold for a vault designed to support uniform plus concentrated loads can be made by placing point loads on a flat fabric sheet (above left) prior to placing a uniform load of concrete. The result is the mold shown (above center) and the shell cast from this mold (above right). A shell such as this could support, for example, both its own dead-weight and that of a raised-floor structure placed upon it.

The “flying” vault shown below is formed by holding a flat fabric sheet from three points while pulling outwards on the fourth point (below, top left). The mold formed by such a rig (below, middle left) produces the vault shown below. This vault spans by resisting the precise inverse of the forces experienced by the loaded fabric membrane during the formation of the mold.

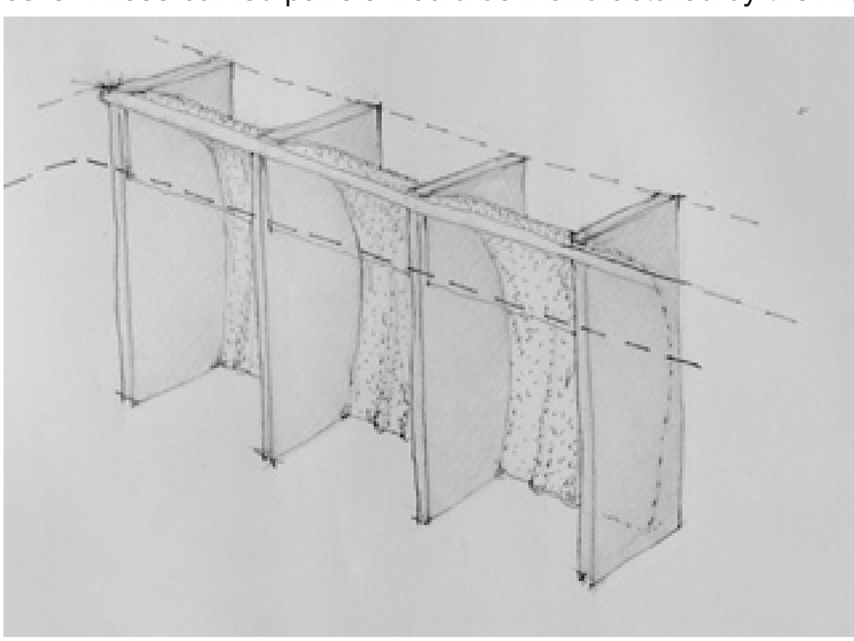
PART 2:

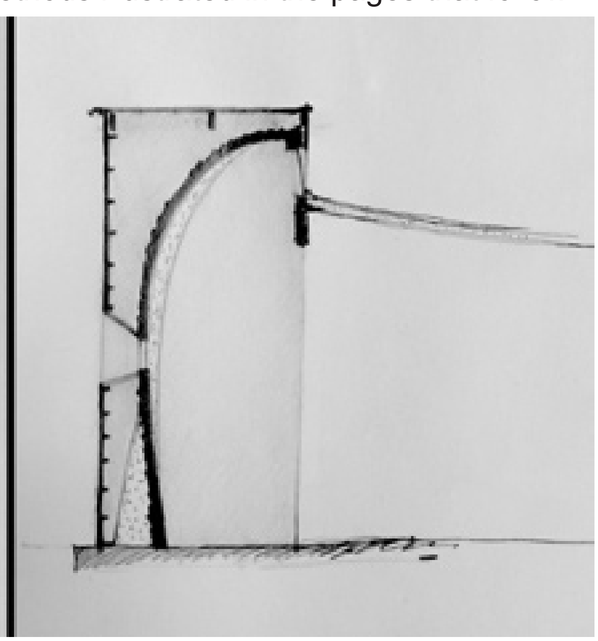
PRE-FABRICATED, THIN-SHELL WALL PANELS FORMED FROM HANGING SHEETS OF FABRIC

For the *Taller de Obras* Project, Open City, Ritoque Chile

The Taller de Obras building has twelve individual drawing “cells” placed around the perimeter of the floor slab. A full-scale mock-up of one of these cells, constructed of plywood at the Open City, is shown in the photos above. Reflected light is brought into the drawing space by a clerestory window and the curvature of the cell wall.

The drawings below show a proposal for fabric-formed thin-shell concrete panels to be used in these cells. These curved panels would be manufactured by the methods illustrated in the pages that follow.





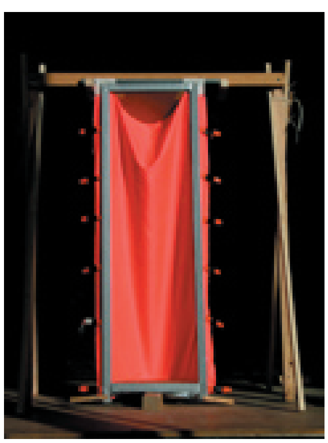
THIN-SHELL PANELS CAST FROM SHEETS OF HANGING FABRIC

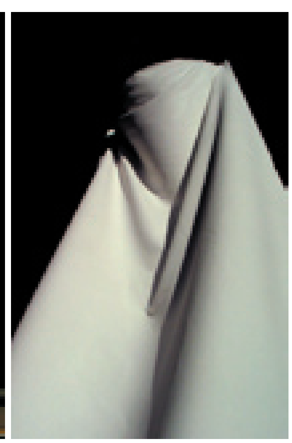
Lafarge Precast Factory, Winnipeg, Canada -- April 2007

A hanging sheet of woven polyolefin geotextile fabric can be used as a mold to produce thin-shell wall panels. The panel shown above uses very little concrete. It is only 5 cm (2 in.) thick. The perimeter edges are 10 cm (4 in.) thick, reinforced with one 15 mm steel rebar on each of the four sides.

It gains its rigidity and strength from its deep folds and double curvatures. It is made by spraying a fiber-reinforced concrete against a hanging sheet of fabric.

This technology was developed at C.A.S.T. using small working models as illustrated in the three images below. A light nylon fabric was sprayed with wet plaster to form the models shown here. Our model fabric formwork rigs were scaled up for the full-scale tests. This kind of simple scaling up is possible because tension forces scale up linearly (as opposed, for example, to bending forces which increase geometrically, as the square of the span).





The surface of a small-scale plaster model (above left) is compared here with the surface of a full-scale shotcrete panel (above right).

The fabrication of one of these thin-shell fibre-reinforced panels is shown below (left) along with the finished panel (below right).

These tests used flat sheets of an un-coated woven polypropylene geotextile fabric as the formwork. Alternately, a fabric with a smooth plastic coating on one side and a fuzzy non-woven fabric heat welded to the other could be used, so that the hanging fabric would become permanently affixed to the concrete. This would producing a plastic-covered mold to be used horizontally in the precast production of identical wall panels.

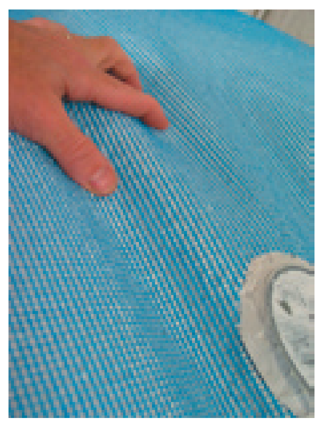
PLASTER WORKING MODELS - ILLUSTRATING PRECAST WALL PANEL PRODUCTION FROM FABRIC-FORMED MOLDS

C.A.S.T. Laboratory 2007 -- for the *Taller de Obras* Project, Open City, Ritoque Chile

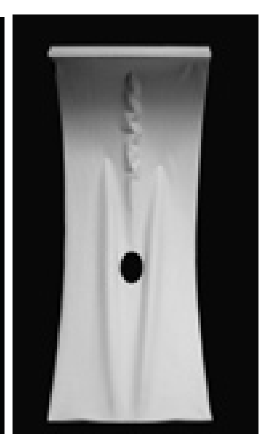
A plastic-coated fabric is hung at an angle and sprayed with plaster to model a sprayed concrete application. The flat fabric sheet is given a series of structural corrugations formed by hanging the sheet over a tension cable placed under the center of the sheet. The deformations of the flat sheet over this cable serve to increase the effective depth of the shell structure.

The mold thus formed is shown (at left) with its smooth plastic surface placed upwards, ready to receive its first “face-coat” of plaster (shown here at right).

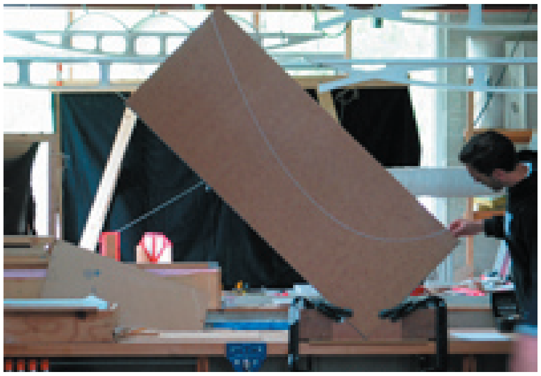
Note that the steel-frame rig used to hang the fabric is now used to support the finished mold - both in turning it over and during precast production.



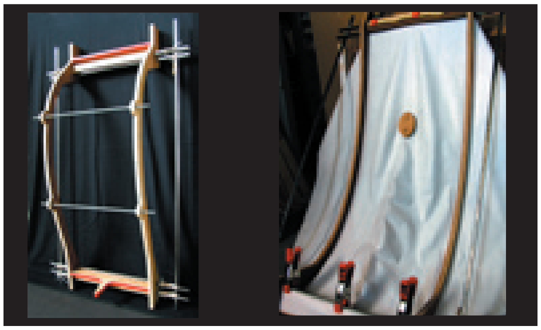
The panel is reinforced with a flat sheet of reinforcing mesh (left). This sheet will naturally conform to the same curved geometry as the panel mold (center and right) because the mold itself is formed from an identically dimensioned flat sheet of fabric.



We separately built up a brace attached the rear of the panel so that it would stand as a self-supporting structure. Note that the vertical edges of this panel are curved and not straight.



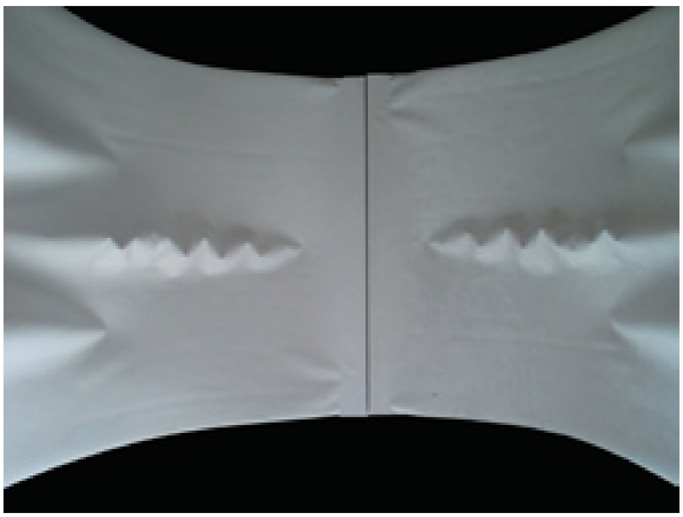
To form a panel with straight and parallel vertical edges, the mold needs controlled, bounded edges, rather than the “free” edges of the mold previously illustrated above. One method of doing this is shown here. A weighted chain is used to mark the desired funicular curve of the edge pieces (top left).



Edge-frame pieces are cut along these funicular lines and the formwork fabric is sandwiched between paired top and bottom edge frames. Plaster is sprayed onto the fabric to form the mold (bottom left, top). The panel formed from this mold (middle and bottom left, and bottom right) have controlled edges on all sides, allowing the simple connection and repetition of identical panels in series.

PART 3:

MODEL STUDIES OF OTHER ARCHITECTURAL POSSIBILITIES



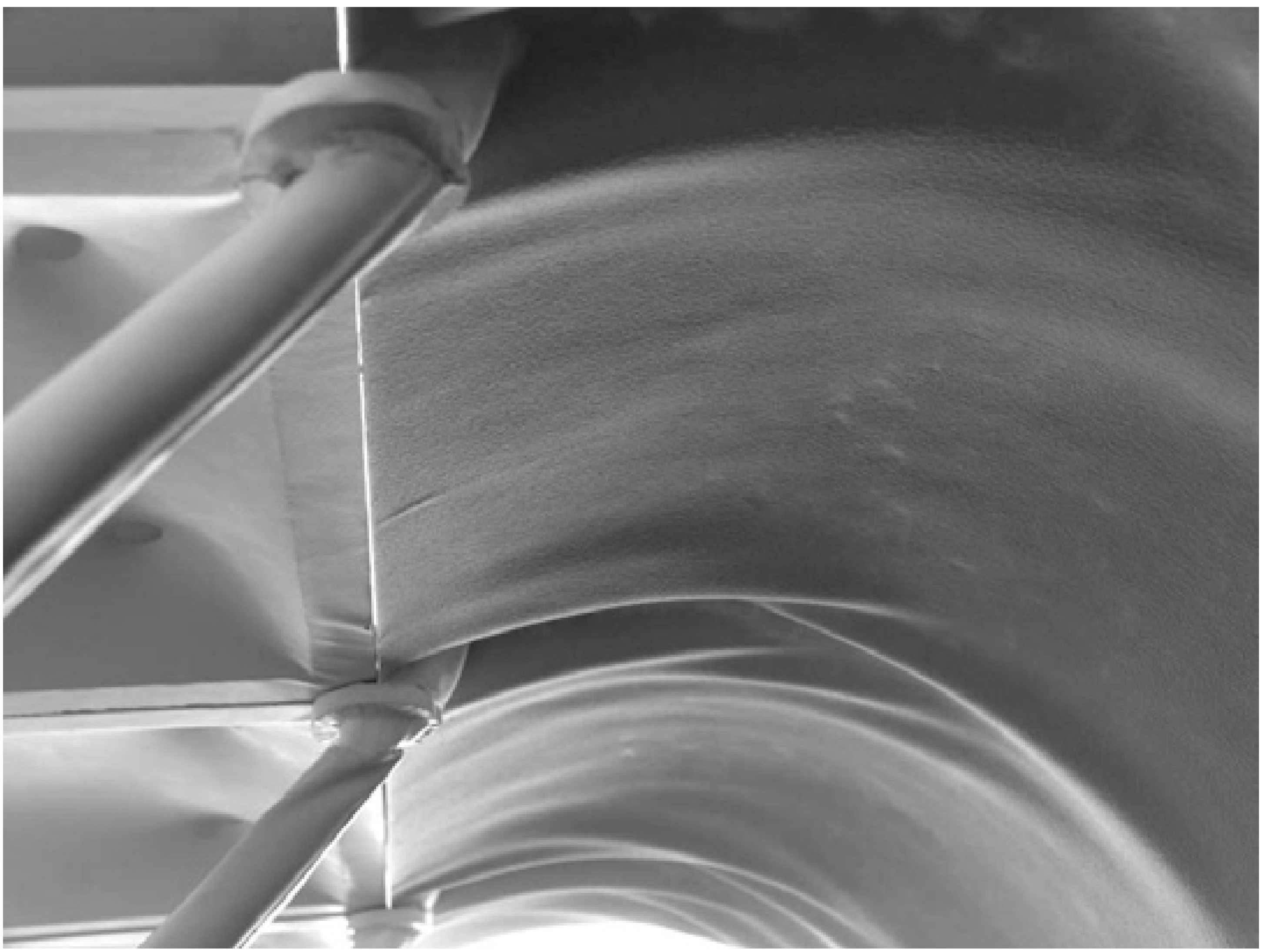
A NEW COMPRESSION ARCHITECTURE

The most efficient way to resist a force is through linear tension. The second most efficient is through compression. The most common structural strategy for industrialized construction, however, are frames in bending, and bending members require far more material to do their work than compression structures. The constructions envisioned here are proposed as efficient, low material consumption structures.

The hIstory of much of the world's architecture is a history of spaces composed through compression shapes -- arches, vaults, domes, walls, and columns. These forms were largely abandoned in the 20th Century in favour of the uniform-section frames and panels of 'machine modernism'. There are both cultural and technical reasons for this profound shift away from the cellular division of space engendered by compression vaults and domes in favour of extensive horizontal spans offered by beams and slabs. This research opens the prospect of a new kind of compression architecture, one that partakes of the great material efficiencies offered by pure compression, yet without the limitations imposed by the closed celuar spaces of earlier compressive forms.

These freely-formed vaults offer the prospect of a spatially ‘free’ compressive architecture. The spaces formed by fabric-formed compression structures are generated directly by the shapes produced by arresting the falling of a fabric membrane. When these ‘falling shapes’ are inverted (turning pure tension into pure compression), the shapes of falling are transformed into forms of levitation. The forces generated during the fabric mold’s production are inscribed and literally *embodied* in the curved surfaces of the concrete structures cast from these molds. The folds and undulations produced in the flat sheets, as they are forced into double curvature tension geometries, produce deep folds that help the structure resist bucking (a potential weakness inherent in thin compression members).

Simplicity of construction, minimal consumption of materials, and great beauty are the natural products of this simple method. New architectural and spatial posibilities are waiting to be uncovered and explored.



Credits:
The plaster models were made at the University of Manitoba's Centre for Architectural Structurea and Technology in Winnipeg, Canada by C.A.S.T's "Team Gravity", Research Assistants Aynslee Hurdal, Leif Friggstad, Mike Johnson, and Kyle Martens who was also responsible for construction of the Open City Wall Panel models. Tom Alston assisted 'Team Gravity' with full-scale construction of thin-shell wall panels. The full-scale Open City floor slab formwork mold was constructed by Bianca Hilbert, Jennifer Reynolds, Rebecca Loewen and Jocelyn Tanner with assistance from Team Gravity.

Special thanks to Andy Dutfield, Peter Schuster, Daryle Kaskiw, Ron Hutter, and Norberto Freylejer at the Lafarge Precast factory in Winnipeg, Canada who's generosity and support made these full-scale tests possible.

This work is deply indebted to the work of two great structural artists, Eladio Dieste and Heinz Isler.