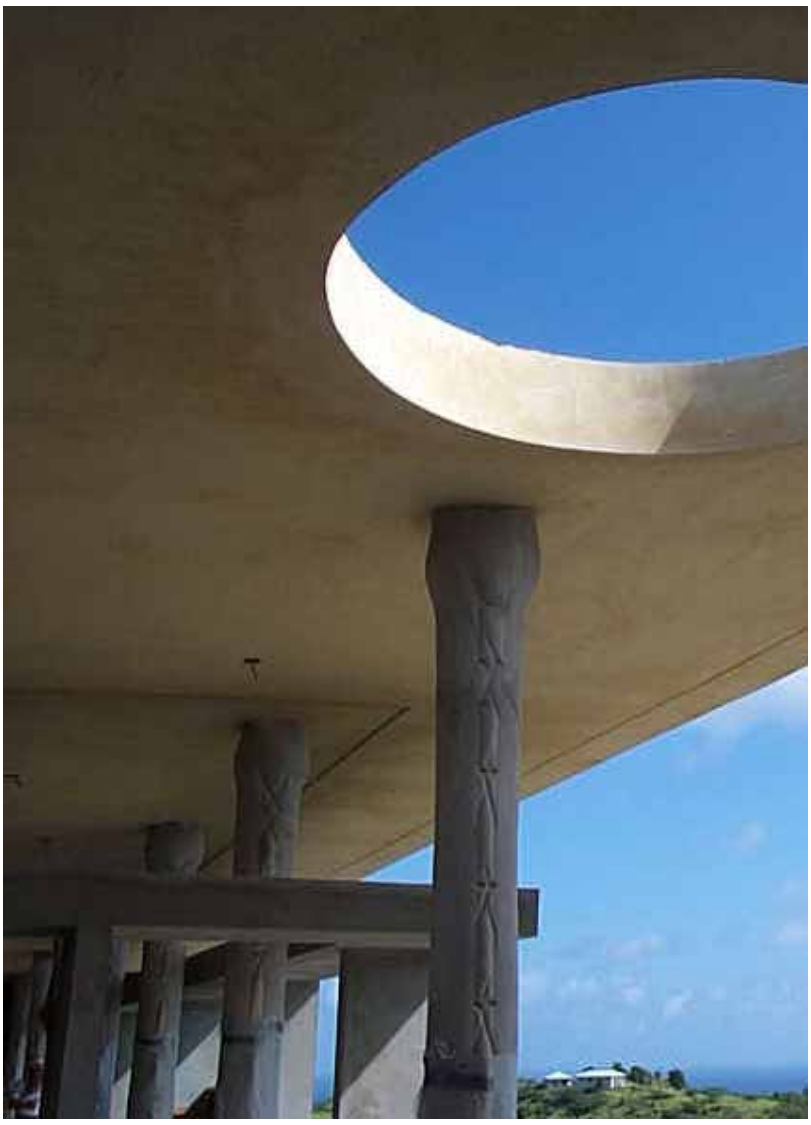

FABRIC-FORMED CONCRETE COLUMNS

FOR CASA DENT IN CULEBRA PUERTO RICO

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This paper describes the construction of thirteen fabric-formed concrete columns for a private villa in Culebra Puerto Rico. Fabric formwork was chosen for this project because of the unique architectural and sculptural capabilities this formwork method provides. Beyond the architectural advantages offered by this method, however, there are several unique technical aspects to this project that are worthy of discussion and which constitute the essential content of this article. Casa Dent represents the world's first use of fabric formwork to cast reinforced concrete columns supporting a flat-plate slab. This formwork incorporates several unique design features with relevance to the development of fabric-formed structures.

Casa Dent, is a 303 m^2 (3,300 ft.^{2}) private villa designed by Fu-Tung Cheng of Cheng Design, with Robert Lawson structural engineer. It is a single story concrete structure with a flat-plate roof slab supported by thirteen cast-in-place reinforced concrete columns. The roof slab is sloped in two directions making each column a different height, ranging from 3.8 m (12'-6") to 2.9 m (9'-8"). All column diameters are a minimum of 34 cm (13.5"). Each of the thirteen column capitals is architecturally unique. The Author was responsible for the architectural and formwork design as well as on-site construction of these columns.

Fig. 1. Fabric columns formworks awaiting concrete placement

Figure 2. Lightweight fabric formwork for 13 individually dimensioned and detailed columns were shipped by air to Culebra, PR in three small duffle bags.

Fig. 3. Typical concrete column cast from fabric formwork shown in fig. 1. Architectural design and detailing are the result of natural deflections in the formwork fabrics caused by the hydrostatic pressure of the wet concrete.

These thirteen uniquely dimensioned and detailed columns were all constructed using a single formwork design. The formwork was constructed from simple rectangular fabric panels sewn into cylindrical tubes. Variations in circumference, height, and capital design were achieved solely by the manner in which this basic cylindrical formwork was "rigged" (figs. 1 and 3). The formworks were fabricated in Winnipeg Manitoba, and shipped by air to Culebra in three small duffel bags (fig. 2).

The following observations are offered at this juncture:
1) With flexible formworks, the final geometry of the cast member is the result of the interaction between the flexible tension membrane and the wet concrete it contains. Unlike conventional rigid formworks, members of high complexity and specificity can be cast from simple, flat, formwork membranes which are allowed to deflect under the load of wet concrete. Furthermore, one such formwork can be used multiple times to form a multitude of differently shaped and dimensioned members simply by altering the manner in which the formwork is rigged. These variations are achieved by furling or unfurling formwork to different lengths, by alterations in support and boundary conditions, and by modulations of fabric prestress levels.
2) Because fabric formworks are extraordinarily lightweight, they can be manufactured anywhere in the world and shipped by air freight to any construction site in the world. This unprecedented degree of geographic freedom opens extraordinary new possibilities for how the constraints of a construction project are conceived. (The formworks for the Casa Dent columns are currently stored under a table in Winnipeg.)

FORMWORK DESIGN

The clients and Cheng Design were offered two basic options for the columns' design. The first, and simplest, was to make the forms entirely out of a high density polyethylene scrim. The other was to use a combination of an outer polyethylene jacket and an inner stretch-knit ("Spandex") liner. The second,

and more complex, option was selected by Cheng Design for aesthetic reasons.

The basic strategy for an in-situ fabric-cast column is as follows: the bottom of a fabric tube is attached to a footing, or in this case to the floor slab (fig. 5), while the top is stretched vertically to a scaffolding structure above (figs. 6). No other intermediate or lateral supports are required. The mild vertical pre-tensioning, provided by hand tightening of the formwork, is all that is required to laterally stabilize a vertical column of wet concrete.

We used the roof-slab formwork as scaffolding for the Casa Dent column formworks. The framing of this deck was standard, except for some special attention to the location and direction of framing members directly above the column locations. The roof-slab formwork deck's 4X4 beams were used as "sheaves" to pull the outer polyethylene jackets upwards (fig. 6). This arrangement allowed the same jacket design to be used for all columns; differences in height were simply taken up by pulling the jacket further (or less) over its 4X4 "sheave". (In other circumstances the formwork can simply be connected at the appropriate height, with the excess fabric being furled out of the way at the top or bottom.)

The Casa Dent columns all use standard steel and concrete designs. The only essential

Fig. 4. Inner liner with outer jacket, prior to jacket lacing and pre-tensioning.

Fig. 5. Bottom of fabric formwork attached to floor slab

Fig. 6. Fabric Formwork fully installed and awaiting concrete placement. Note how the (black) outer jacket is rove over its 4x4 “sheaves” for vertical pre-tensioning. Also note how the (white) stretch-knit liner meets the underside of the roof slab formwork, adapting to in its own specially cut profile.

difference from standard construction is the change in formwork materials. The flexible fabric tubes thus installed entirely replace the rigid steel or plywood box forms traditionally used to cast reinforced concrete columns.

STRUCTURAL COMPARISON: RIGID vs. FLEXIBLE FORMWORKS

In order to hold wet concrete in place along a flat plane, conventional rectangular, panelized, formworks must resist bending moments. Furthermore, prismatic rigid forms must limit deflections to near zero thus requiring significant depth, and hence material and weight, to achieve their requisite stiffness. This structural strategy also tends to produce significant stress concentrations at edge joints where the reactions of the bending forces are gathered and resolved. It will be appreciated that there is a heavy price to be paid for holding a heavy plastic material, like wet concrete flat. Indeed, the vast majority of the material (and weight) in a traditional rectangular formwork is required solely to limit deflection.

Flexible formworks, on the other hand, take a very different approach. A structural analysis of a cylindrical fabric column formwork reveals that the hydrostatic pressure of the wet concrete is taken by the horizontal (circumferential) fibers in tension. The mildly pre-tensioned vertical fibers of the fabric are essentially acting to hold the horizontal fibers in place, and to laterally stabilize the vertical column of wet concrete. This is the simplest and most efficient containment structure imaginable; all forces are resolved through tension alone, allowing the use of extraordinarily lightweight membranes that naturally assume minimum surface funicular tension curves to accomplish their task.

The efficiency of such an approach simultaneously produces new degrees of architectural and sculptural freedom. Previously unimaginable shapes are accomplished by the “form-finding” actions of tension membranes under load, suggesting the emergence of new concrete architectures that embraces the fluidity of concrete rather than struggling against it.

FINISH

Another advantage of using fabric membranes to contain wet concrete is improved surface finish and strength. Permeable fabric membranes can act as a filter, allowing air bubbles and excess mix water to bleed out, thus gathering a cement-rich paste at the surface of the cast member. The loss of excess mix water can also increase the strength and durability of the concrete. In the author’s experience excellent finishes can be obtained using a wide range of mix designs and permeable fabric membranes. The Casa Dent columns, however, were very instructive with regard to the impact of mix design on surface finish and compaction and the advantages of a thin formwork membrane in identifying and remedying potential surface defects.

Fig. 7. Concrete column shaft showing finish free of bug holes, but with slightly 'blotchy' appearance due to uneven nature of concrete mix.

Fig. 8. Column capital showing the impressions left by the torsion or the inner stretch liner, and the fine surface finish obtained by the filtering action of fabric formworks.

The mix design for the Casa Dent columns, as specified by Cheng Design, contained random fibers, and it is suspected that these fibers were at least partly responsible for some surface finish problems encountered in this job. Large clumps with a very stiff, clay-like consistency occurred amidst the otherwise properly plastisized concrete. It is suspected that the cause of these clay-like lumps may have been due to an excessive absorption of water by insufficiently dispersed fibers. This was a consistent problem throughout the three separate pours we did.

The first columns poured presented significant problems with proper compaction of the concrete at the surface of the forms due to these inconsistencies in the concrete. Once alerted to this problem, the formworks were subjected to vigorous external vibration in later pours, thus alleviating further significant difficulties with surface finish. This example illustrates further advantages offered by the flexibility and thinness of fabric formworks: 1) The stiffer clumps of concrete in the mix could be readily felt through the thin formwork membrane, allowing an immediate diagnosis of the problem with the mix. 2) We could target our external vibration directly at the problem areas which could be easily identified by feel. In this way, a thin flexible form allows a kind of haptic "vision" where one can "see" through feeling the consistency of the concrete inside the formwork mold. 3) Vibration can be aimed precisely

Fig. 9. View of a column fabric formwork meeting the top of the roof slab formwork deck. The (dark blue)stretch knit liner is seen attached to the center of a plywood ring that is free to rotate in the roof formwork deck.

at problem areas. External vibration can be achieved manually by "massaging" the flexible membrane. Manual vibration can take the form of shaking, patting, or pounding the formwork surface as required.

TORSIONAL CONTROL OF DEFLECTIONS

One novel aspect of the Casa Dent column formworks was the use of torsion to control deflections of the formwork membrane. Torsional control was used in the top portion of the inner fabric liner forming the column capitals.

Because the hydrostatic pressure exerted by the wet concrete is very low towards the top of the column, great geometric freedom is possible in the formation of column capitals. This is particularly true when using highly elastic "stretch knit" liners such as Spandex. In previous applications deflections in capitals formed in stretch knit liners were controlled primarily through local vertical pre-tensioning regimes. This method of modulating capital deflections was impossible to use in the Casa Dent formwork because vertical pre-tensioning of the stretch-knit liner would interference with the placement of reinforcing steel in the flat plate roof slab. Another method of locally modulating deflections in the column capital was sought, and the use of torsion was chosen as much for its aesthetic effects as for its technical usefulness (Fig. 8).

The device for controlling capital deflections, though elegant in its own way, was the most complex portion of an otherwise simple formwork design. The description of this device is as follows:

The outer polyethylene jacket was pulled away from the inner Spandex liner near the top of the column by the placement of the upper scaffolding supports, as can be seen in fig. 6. This left the inner stretch knit liner unsupported by the outer jacket near the top of the column, i.e., in the area of the capital.

The top of the inner "Spandex" tube was attached to a circular disk cut from the plywood of the roof slab formwork. A hole was cut in the center of this disc to receive the inner liner (fig. 9). This hole was specifically cut so that each capital had its own individual profile as it meets the underside of the flat plate roof slab (see fig. 6). The circular plywood disc, with the inner liner attached to the hole in its center, was free to rotate within the plane of the roof slab formwork (fig. 9). By rotating this disc, a torsion was applied to the inner liner of the column formwork, thus producing a greater or lesser degree of horizontal restraint in this portion of the formwork. By adjusting the degree of rotation, one could alter the extent to which the inner liner would deflect outwards when filled with wet concrete; one could literally "dial a deflection" for an individual column capital.

CURRENT STATUS AND OTHER RESEARCH

Casa Dent is currently under construction. A completion date has not been set.

Fabric formwork research in other areas is ongoing at the

University of Manitoba's Centre for Architectural Structures and Technology (C.A.S.T.). Current projects include the development of a system for precasting concrete shell and vault panels using prestressed fabric formworks. C.A.S.T. is also collaborating with the Catholic University of Valparaiso in Chile in the design of a fabric-cast building to be constructed in Ritoque Chile.

Fig. 10. View of Casa Dent interior under construction.

REFERENCES

[1] The author has produced fabric-cast concrete columns, beams, slabs, and panels in pre-cast and cast-in-place applications. A system for casting cast-in-place fabric-formed walls has been developed by the Japanese architect Kenzo Unno. The work of Spanish architect Miguel Fisac is also of interest in this regard. Publication lists and other information on fabric-cast architecture and concrete structures can be found at: http://www.umanitoba.ca/faculties/architecture/ under "Research", then, "C.A.S.T."

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