Material Computation

VOUSSOIR CLOUD

Lisa Iwamoto
IwamotoScott Architecture

Craig Scott
IwamotoScott Architecture

Intermittently throughout architectural history, whether weighted toward constructive necessity or design agenda, architects, engineers and builders have employed structure as the imperative that connects material with form. From traditional masonry construction to geodesic domes, this method of form making is largely dependent on geometry, the single most important factor in determining structural performance. Arches, vaults, domes, thin shells, tensile membranes, cable nets and the like intricately unite material with surface structure. The ultra thin concrete hypar roofs of Felix Candela and catenary domes of Heinz Isler, Eladio Dieste's sinuous brick walls, and Frei Otto's wood lath grid-shells and steel cable nets are modern examples that celebrate the coupling of material behavior with structural surface geometry. These architects employed extensive physical form-finding such as hanging chain models, plaster mesh casts, and cable nets loaded with weights carefully monitored by strain gauges to achieve optimized structural solutions.

In contrast to such structurally pure models, the power of computation has opened possibilities for at once muddying and synthesizing geometry, structure and material performance. Where the earlier twentieth century experiments employed a more or less uniform tectonic based on symmetrical structural diagrams, contemporary analysis and design techniques can efficiently adapt a material system to address variable, localized, and non-symmetrical loading conditions. This has resulted in projects characterized by non-optimized structural forms that register the impacts of geometry on material behavior with a deviated tectonic system.

IwamotoScott's design research does not explicitly pursue a tectonic agenda, but rather attempts to achieve a synthetic outcome by negotiating material and surface with environment and space, geometry and form. The work uses structure as a predominant, but non-determinative constraint. Voussoir Cloud (Figure 1), our installation at the SCIArc Gallery in 2008 extends this research and draws from the methodology of the aforementioned historic and contemporary precedents. However, rather than the design process being determined either by the structural and material optimization pursued by the architects/engineers of the mid-twentieth century, or by a deviated constructional system based on non-optimized forms in the latter examples, Voussoir Cloud began with research into material behavior. The original design intent was therefore not formally motivated, but evolved from empirical testing of a material and determining its salient relationships to geometry and structure. The material selection stemmed from a previous project, In-Out Curtain, which was made from folding micro-thin wood and paper laminate. For Voussoir Cloud, we were interested in de-familiarizing this normally common and basic material, wood, typically used either as decorative skin or trabeated structure, as skin and structure simultaneously. The unexpected combination of a wood product being paper thin and having shear strength, translucency and the ability to fold propelled the qualitative aspects of the design.

The design process for Voussoir Cloud began similarly to In-Out Curtain, by folding sheet material into a three dimensional modular component. In this case, however, we sought to

Fig. 1

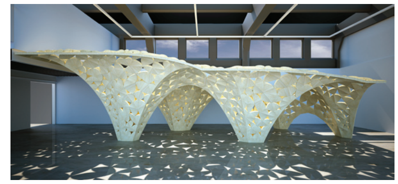

Fig. 2

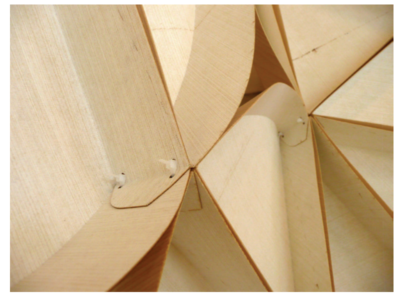

Fig. 3

Fig. 4

explore the possibilities of folding along a curved seam. Small handmade models were used to test geometric relationships across the fold in plan and section (Figure 2). It was relatively simple to determine that the greater and more acute the curve in plan resulted in a higher degree of curvature in section, but finding accurate dimensional relationships between the two was significantly more complicated and became central to the digital design process. What also became apparent from these physical experiments was that any aggregation of the modules, or petals as we referred to them because of their shape, produced a naturally curving surface. By assembling a number of small mock-ups from simple hand drawn plan patterns using diagrid and Delauney tessellations, it was evident that both types of triangulation resulted in overall arcing of the surface due to the outward bowing out of the flange along the curved seam (Figure 3). This vaulted nature ultimately dictated the overall form and design strategy.

From here the design process developed along two parallel tracks. The first aimed to translate the material behavior of a single petal into a digital script based on a set of geometric relationships; the second to determine overall form. In designing the form the project took on many variations, however certain design intentions remained consistent throughout. These included the desire to create an occupiable and atmospheric environment in the gallery rather than a discrete object, and to have the installation be equally compelling from above as from within. Driving this concern was that a primary view of the gallery space is from above via a frequently traversed walkway at mezzanine level.

The final design fills the gallery with vaults whose billowing character and constructional system is revealed from above. The plan is based on the typology of the peristyle hall, but adapted to produce scalar, spatial and tectonic effects. The columnar and volumetric organization takes advantage of the contemporary capacity to inflect as opposed to the static, regularized definition typical in both classical and modernist buildings. Using edges of the gallery as spatial and constructional constraints, the vault edges are supported and delimited by the entry soffit and two long gallery walls. The vaults modulate in scale and proportion, having greater density at the edges and toward the rear of the gallery, forming a progressively compressed and varied space (Figure 4).

The geometry of each vault is structurally derived; however, the seemingly obvious connection between the vaulted surface of the petals, and a structurally vaulted form was not immediately apparent. It took multiple failed design attempts working with the curved surfaces as a structural panel system applied to a singular form to move to a process of structural form finding. Once this methodology took hold, the conceptual premise of the project became more focused in its aim to create a voussoir cloud by exploring the structural paradigm of pure compression coupled with an ultra lightweight material system.

As a form finding enterprise, the project draws significantly from the work of Frei Otto and Antoni Gaudi who used hanging chain models to find efficient form. Under their own weight,

Figure 1. *View of final installation inside gallery*

Figure 2. *Interior elevational perspective render with gallery wall removed*

Figure 3. *Connection Detail*

Figure 4. *Gallery installation*

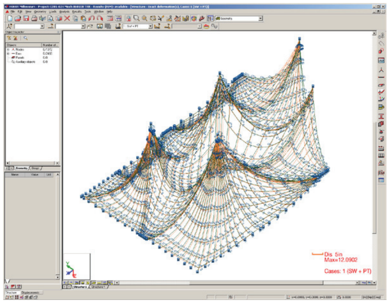

Fig. 5

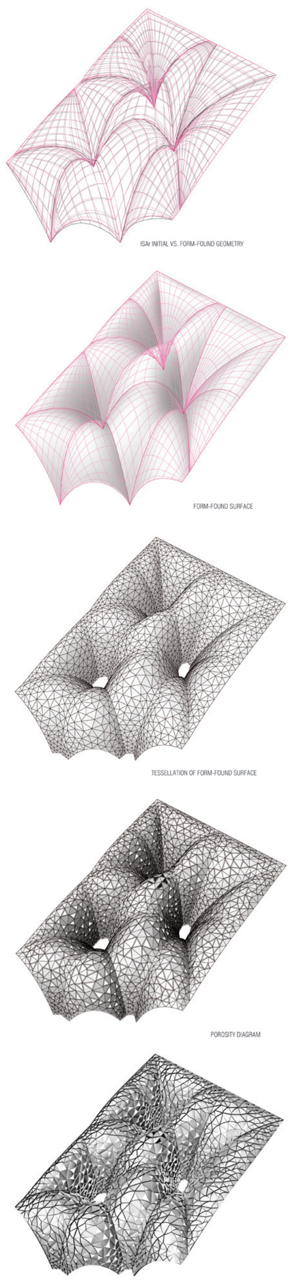

Fig. 6

Figure 5. *ROBOT hanging chain*

Figure 6. *Form found vault*

hanging chains naturally adopt a funicular profile with minimal internal stress; they are in pure tension with no shear or bending forces. If re-inverted, the tension becomes compression creating a pure catenary arch. We worked closely with the engineering firm Buro Happold in Los Angeles to arrive at a funicular configuration for the vaults though an iterative digital design process. Each version began with our office first creating a three dimensional digital model articulating the vault edges with approximated catenary arches. This model was then given to Buro Happold, who literally turned it upside down to evaluate the curves as a network of digital hanging chains. The engineers used the structural analysis program ROBOT to find the new catenary geometries using non-linear analysis; this allowed the curves to deform under a uniform self-weight, computationally mimicking a hanging chain. For the final curves, the displacement between the initial and the form-found geometry was up to twelve inches, and the form-finding process reduced the bending and deflections in the structure by ninety percent **(Figure 5)**. IwamotoScott used the pure catenaries from Buro Happold to generate the surface geometries of the vaults. These surfaces were first approximated in Rhino then shaped into funicular shells using another form-finding script in Maya **(Figure 6)**.

Structurally, the vaults rely on each other and the three gallery edges to retain their pure compressive form. This overall system is stable because adjacent vaults are in equilibrium at their intervening seams; the outward thrust of one vault is balanced by the equal and opposite force of the adjacent vault. The seams also function as a pathway for the compressive force in each vault to travel down to the gallery floor where the fourteen segmented pieces resolve to make a series of five columns supporting the interior and back edge. It is a highly interdependent set of elements that gently push on each other to maintain stability.

This interdependency is multiplied at the level of the tessellation where the individual petals work together to form the larger vaults. For the system to work as a whole, each individual petal must perform structurally. We again used geometry to maximize the material's structural performance. The three dimensional petals formed by folding thin wood laminate along curved seams develop stiffness and stability from otherwise flexible material. The curve also produces a dished petal form that uses the internal surface tension of the wood and folded geometry of the flanges to hold its shape. At the same time, the flanges want to bulge out along the curved fold. This curvature ultimately afforded a way to attach the petals together using the surface area of the flanges for bearing **(Figure 7)**. Unlike a triangulated pattern where modules would meet at a single end point, this bearing surface allows the modules to press upon each other and therefore work in compression. The bulging petal edge is also what affords the vaulted structure porosity; the curvature is only possible if there is an adjacent void.

The most challenging step was deciphering and digitally scripting the proportional relationships between the curved fold-line in plan and the resulting sectional deformation. From the models we could establish that the sectional deformation of the petal is related to the plan curvature and degree of bend, but by what amount exactly? It was also clear from the physical models that we could create the three dimensional dished module with a non-doubly curved surface, but this proved difficult to digitally define. We were fortunate to discover a solution in a paper titled "Folded Developables" from which we could discern key geometric principles (Folded Developables, J.P. Duncan and J.L Duncan, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 383, No. 1784, September 8, 1982, pp. 191-205.) One key determinant was that if the flanges of the petal are perpendicular to the original cell surface, the maximum curve offset, or delta, from the original triangular cell in plan is the same as the maximum delta in section.

We also gleaned from "Folded Developables" that at any other flange angle than ninety degrees, the amount of sectional dish in section varies with the plan curvature according to a logarithmic function. This was important because the sectional change affects the final plan dimensions; the higher the sectional dish, the smaller the petal size in plan – which again affects the accuracy of how they fit together. In the case of Voussoir Cloud, none of the flange angles are at ninety degrees. They are dictated by the normals of the vaults rather than the cell itself, so the amount of petal dish, and therefore its size, has a unique geometry that needs to be calibrated to fit into the overall arched form. Though mathematically, the relationship of flange angle to sectional height is non-linear, we felt confident in simplifying it to a simple percentage based on our physical tests. Here, we relied on the forgiveness of the material to accommodate the small imperfections of final petal size to original plan triangle.

From the proportional and geometric data we developed a script that managed the petal edge plan curvature and instantiated the three dimensional modules into our tessellated surface. A second script was developed to unfold, label, score, and add holes for fasteners. The only manual pre-assembly activity was nesting the modules on the 4 x 8 sheets for laser cutting. While we sought material economy here, it was also critical that the unfolded petals align properly with the grain of the wood. Wood is a non-isotropic material, more flexible along the grain and resistant to bending against. Though there was only a micro-thin layer of wood on our wood/paper laminate, the grain had a dramatic effect on the ability of the petals to dish. The grain had to be aligned to the long direction of the petal or longest side, or perpendicular to the short side in order for the petal to form properly. Ultimately, each petal behaves in a slightly different manner based on its size, edge conditions, and position relative to the overall form; it is here that the two scales of exploration -- module and form -- merge.

Combining the structural and modular geometries was largely a packing problem. We sought to organize the petals for the greatest functional and perceptual performance. Each vault was tessellated using Delaunay triangulation. We chose this pattern because it is at once visually informal and can capitalize on structural logistics. There is greater cell density where smaller more connective petals are grouped together at the column bases and at the vault edges to form strengthened ribs, while the upper vault shell loosens and gains porosity (Figure 8). The petals have greater offset and more curvature at the top where there is more porosity, creating the dimpled effect on the interior.

Once the petals were instantiated, Buro Happold again employed ROBOT to conduct a finite element analysis of the tessellated structure to test its performance and ensure that the load values and the load path were as predicted. In some instances, the seams needed to be strengthened sponsoring us to create a vertical load path by having the petals weave back and forth across every continuous seam. As a part of refining the petal organization, we built several full-scale mock ups of a single vault. These were used to affirm structural viability and develop connection methods for the petals. The size, density and porosity of the final petals were a direct response to digital and physical analyses.

Once the overall geometry, structure, tessellation, and material system were aligned, the actual fabrication and final assembly at SCIArc was an exercise in scheduling and material management. The 2,300 petals were cut off-site in Michigan near the material manufacturer due to cost and equipment considerations; the laser cutter could handle 4 x 8 sheets yet power down sufficiently so as not to burn the material while scoring. The pieces arrived in batches which the SCIArc students sorted, folded and glued.

In the end, Voussoir Cloud attempts to reform both structure and material to create new readings of a traditional architectural typology and construction method. Vaults are modulated and adapted to new plan and material configurations. These inflections are made possible by computational methods that model, structurally analyze, and organize large quantities of non-uniform elements. It is with considerable effort in the physical realm, however, that the conceptual and experiential goals of the project are made manifest. Material exploration was essential in the derivation of the architectural idea. The petals -- our reconstituted "voussoirs" – are light, paper-thin surfaces made into compressive elements. Their fluctuating visual quality from solid wood block to thin luminous surface as material affect drove the atmospheric intentions of the project (Figure 9). It is the perceptual performance of Voussoir Cloud that makes it at once visceral and immediate, and instigates more considered speculation that our goals for the project ultimately lay.

Note

This paper is a shortened, edited version of the text, co-authored with Craig Scott, which was included in the "Matter: Material Processes in Architectural Production" book edited by Gail Peter Borden and Michael Meredith and published in 2011 by Routledge from London.

Fig. 7

Fig. 8

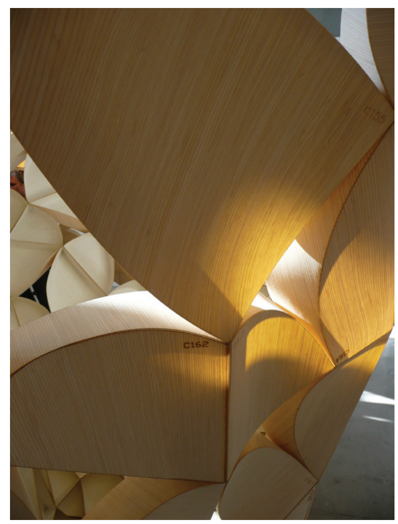

Fig. 9

Figure 7. *Lighting Detail*

Figure 8. *Installation Interior*

Figure 9. *Lighting Detail*