Digital Fabric

GENERATING CERAMIC CATENARY NETWORKS

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Digital modeling in the design environment has prompted intuitive shaping of architectural form. The pliability of the imagination allows limitless possibilities of shape without a constrained methodology. This paper chronicles a design exploring catenary form-finding using parametric constraints in a dynamic modeling environment. Catenary structural networks are treated as digital cloth objects. Applying parametric edge and point constraints simulates various behavior patterns under gravity load. The integration of real-time Finite Element Method [FEM] and dynamic cloth simulation presents an intuitive method for the design and analysis of catenary structures. Constraints resist the limitless pliability of shape and hone the intuition using force to find form realized as a ceramic catenary network.

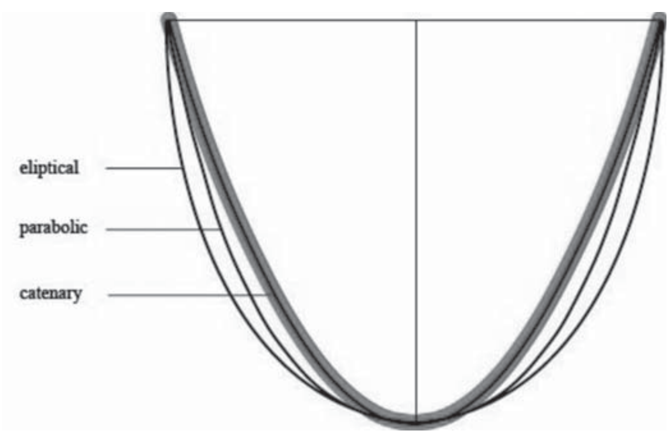


FIGURE 1 Catenary curve diagram showing relative difference between elliptical, parabolic, and catenary curves

DIGITAL HEURISTICS

Popular architectural shape making glorifies hermetically sealed organelles. Unfortunately this glorification often lacks a material and structural logic. Defining a digital logic and material resistance to emerging design and fabrication technologies is fundamental to the education of the architect and indeed the future of our discipline. Few would argue that there are profound ramifications for the discipline of architecture as the field continues to digitize; finding an ethic within the digital process is necessary if there is to be a meaningful dialogue regarding the nature of these emergent methodologies.

We are seeking materially effective solutions defined by empirical investigation and explored in a digital environment. The ambition of this research is not to make a structural system more efficient, but rather to explore further potentials of form generation from an informed structural base. The work is a negotiation of the figural aesthetic based on gravitational loading and the structural stability. It is a methodology that seeks equitable ground in the search for form and structure. The digital environment is more material than tool. The assembled molecules of the digital material are affirmations and denials, ones and zeros, strung together in sequence. To become a tool, material must be shaped, and given weight and response. The introduction of parametric modeling and dynamic simulation allows for the implementation of intuitive shaping of the digital material resulting in a resistance to the essentially limitless possibilities of digital form.

Enrico Fermi developed stochastic modes of inquiry in the early 1930's. Fermi's method of statistical simulation used random numbers and time variables to produce statistically probable results. Developed to simulate nuclear ballistics, the Monte Carlo Method, named after the casino and based on statistical probability, was a direct result of Fermi's initial simulations. The use of Monte Carlo algorithms increased significantly alongside the development of the electronic computer in the 1940s. These algorithms, based on statistical probability, random number variables, and boundary conditions, established the foundation for modern digital dynamic simulation (Metropolis 1987).

Mathematically, parametric equations express a set of quantities as explicit functions of a number of independent variables (Weisstein). The digital design environment can easily manipulate these functions both graphically and numerically allowing the creation of multiple versions with real-time representation. A powerful pedagogical tool, the parametric design environment directly relates complex variables to formal geometry where structural viability can be empirically tested through both digital and analogue modeling.

Until recently, designers used several software platforms to generate form, perform dynamic simulations, provide structural analysis, and create files suitable for computer aided manufacturing. AutoDesk's Maya (formerly Alias Wavefront Maya) platform includes a suite of dynamic simulations and parametric constraints. With the integration of CS-FEM, a plug-in developed for Maya that provides real-time structural analysis, Maya has become a truly immersive digital design environment. Integrating parametric modeling, dynamic simulation, and real-time structural analysis form a possible foundation for digital empiricism: a heuristic design environment integrating layered stochastic models. The development of a digital heuristic for form generation based on dynamic simulations and structural analysis provides a mode for materially efficient form finding.

CATENARY MODELING

In 1675 Robert Hooke observed, "As hangs the flexible line, so but inverted will stand the rigid arch" (Block 2006). By hanging a chain from two points, each segment of the chain, as is the whole, is in pure tension. Figure 1 shows the catenary curve in relation to the parabolic and elliptical curves. Inverting the chain, the links, as in the whole, are in pure compression and the catenary

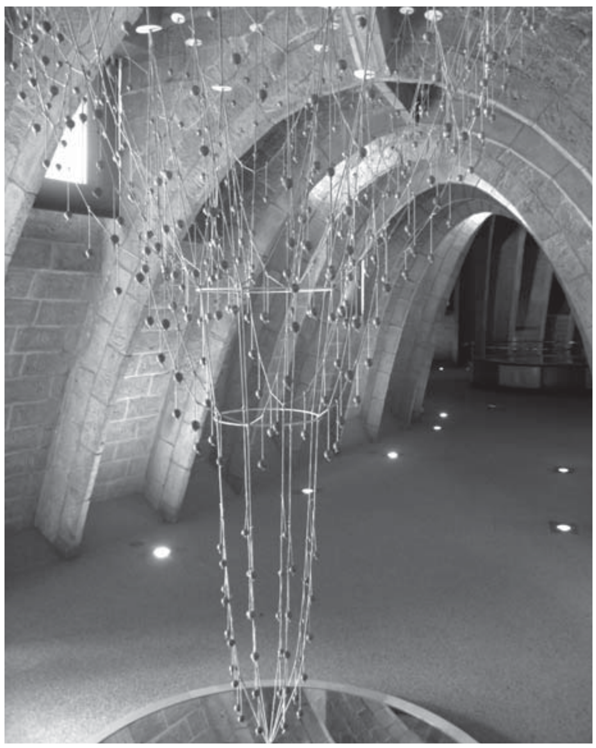


FIGURE 2 Catenary string model showing method for form finding of optimal force path network per given loading condition

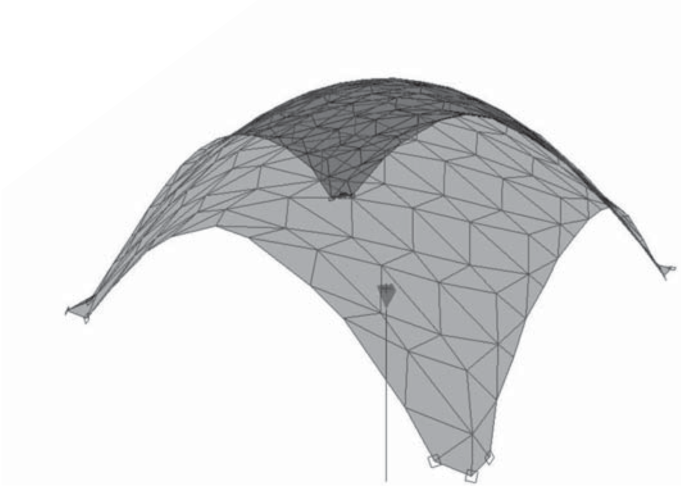


FIGURE 3 Catenary network drape form using dynamic cloth simulation

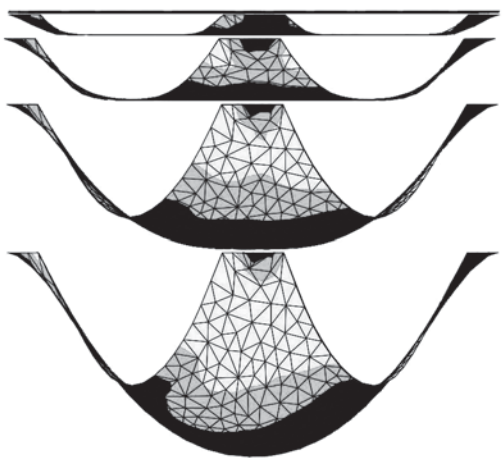


FIGURE 4 Cloth catenary model composite showing stages of draping simulation

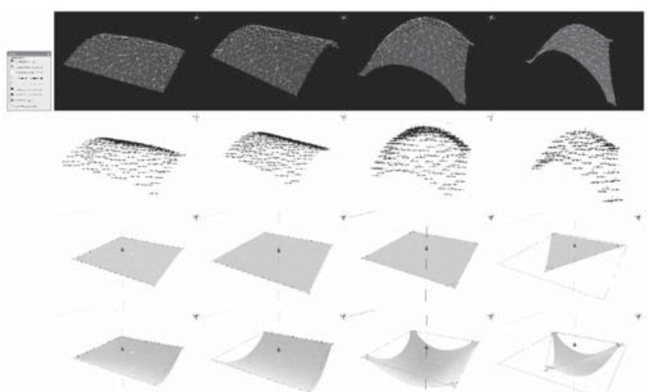


FIGURE 5 CS-FEM form analysis showing constrained edges and points

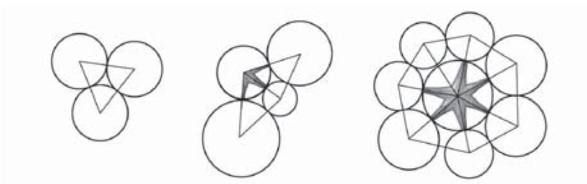


FIGURE 6 Diagrams of relationship of aperiodic packing patterns and edge length

is the shape that the simply supported chain assumes under a uniform gravity load. In 1691 mathematicians Leibniz, Huygens and Johann Bernoulli, in response to a challenge from Johann's brother Jakob, defined the equation for the catenary (from the Latin *catena*, chain) curve. The catenary is a minimum energy form; as a system it assumes the most effective form per loading condition (Westfall 1980).

Barcelonan architect Antoni Gaudi y Cornet, 1852-1926, innovated the use of funicular curvature derived modeling for structural resolution. At first glance it seems absurd to layer complex algorithmic computer models to find solutions that Gaudi essentially proposed with string and sandbags. It begs the question: why hasn't Gaudi's method been more widely used? Perhaps it is that contemporary building systems and modern building codes disallow the sole use of empiric construction systems to determine structural resolution. Further, contemporary building systems are required to resist seismic loading and must be able to absorb dynamic forces (Permanyer 1997). Typically, digital modeling is used as a means of form generation without structural constraint, or conversely as a rigorous means to analyze a pre-designed form as a structural system. Our work is a digital analogue to Gaudi's experimental use of string.

DEVELOPING A CATENARY NETWORK

Cloth simulation in Maya is a digital tool capable of producing complex catenary forms. While catenary equations are deterministic, dynamic simulations are stochastic and based on approximations. The project details one possible resolution for defining a structural system developed heuristically by overlaying dynamic cloth simulation, structural analysis, and dynamic solid body modeling.

A cloth panel is assigned to a set of closed curves in Maya. This panel signifier allows a designated resolution factor and defines the mechanical properties of the cloth. The cloth is defined to closely approximate a frictionless net, showing the least internal bending resistance to gravity loads.

CLOTH ATTRIBUTES:

- The U Bend Resistance/ V Bend Resistance parameter affects the rate at which the cloth bends at vertices, or the stiffness of the cloth. These two properties have a scale from 0-100 and since all four corners of the square cloth object are restrained both are set to at 0 to allow the cloth object to find an optimized form.
- The U Stretch Resistance/V Stretch Resistance parameter affects the rate at which the edge lengths of the polygons within the cloth object increase. These param-

eters have a scale from 1 to 100. In order to find an optimized catenary shell, these two scales are both set to 1.

- The Shear Resistance parameter controls the distance that vertices within the cloth object are allowed to move relative to other vertices. Shear resistance has a scale from 1 to 100. The shear resistance is set to 10.

All other Maya cloth parameters are kept at the default setting. Before the cloth is draped the corner vertices of the cloth object are selected and a drag control is assigned to them. The drag control defines the movement of the selected vertices on a set path. Since the vertices are fixed so the rest of the object can deform into shape neither the movement nor path is pre-defined.

FINITE ELEMENT ANALYSIS

Structural solutions to geometric models are typically sought using FDM, Finite Difference Method, FEM, Finite Element Method, and FVM, Finite Volume Method. Each method generates an approximate solution. CS-FEM modeling works as a real-time analysis of the stress on structural members within a structural assembly, based on material strength and structural configuration. Once material properties are parametrically linked to components, the form can be altered to give immediate results for the local stresses for the new form. The ability to redefine form according to real-time structural input with CS-FEM and Maya is truly a digital heuristic mode for form derivation.

In CS-FEM the material properties and cross-section of each component are entered and a uniform load is applied. As the form is altered the structural pieces are evaluated and tuned to the structural forces, providing an economy of material, cost and time to the design process. FEM modeling greatly increases the potential number of structural configurations possible allowing the design to be tuned specifically to the transfer of stress within the structural assembly. The stress network creates vectors for the alignment of structural components. As a heuristic mode this allows structural systems to be designed prior to form designation and based upon material, module, or other relevant physical criteria rather than the typical method of first designing a form then trying to fit an appropriate structure system, components and materials.

In the search for accuracy of form, defined as the optimized materially efficient solution per loading pattern, using cloth simulation to derive complex catenary-based geometries gives credibility to digital empiricism. There is a compelling reason to use cloth generation to derive a catenary chain: cloth simulation is an algorithm process based on force reaction, making the structural analysis of dynamic models more accurate than non-dynamically generated models. The catenary contains the a priori knowledge of the solution; the form speaks to material efficiency through the nature of force resolution.

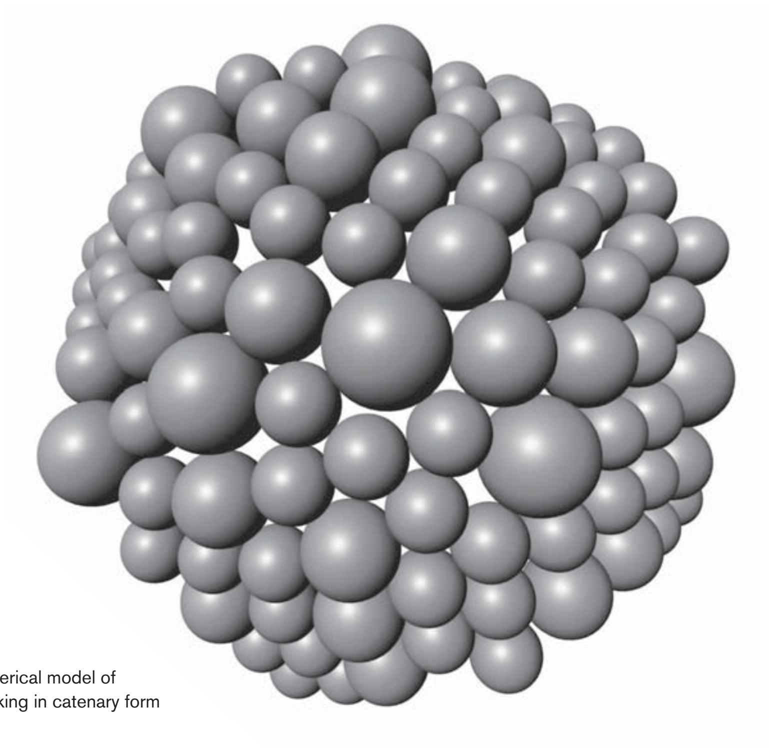


FIGURE 7 Spherical model of aperiodic packing in catenary form

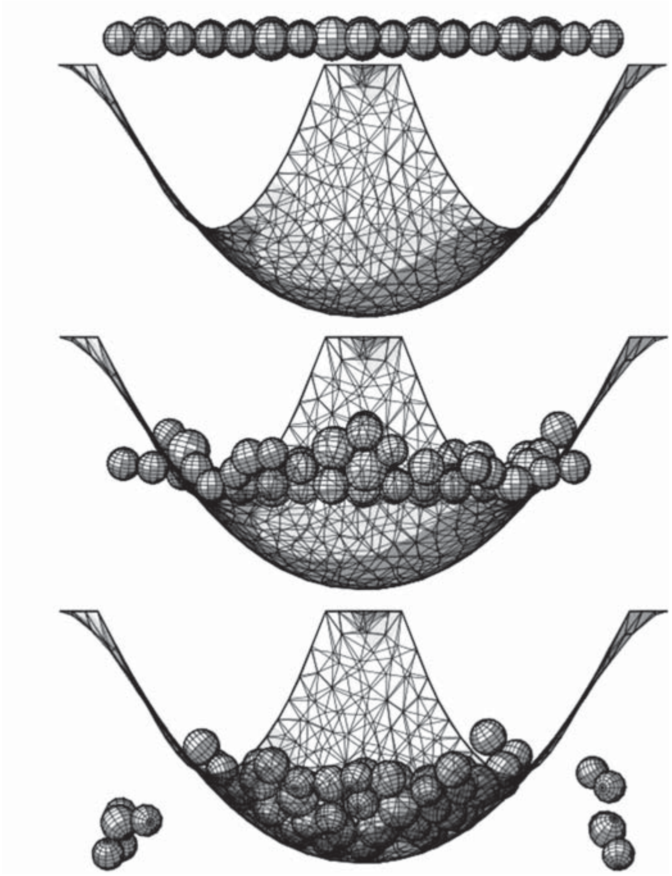


FIGURE 8 Illustration of solid body spherical packing simulation

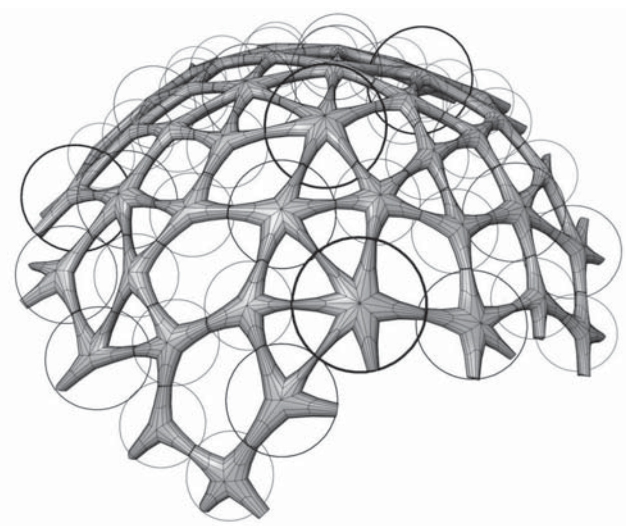


FIGURE 9 Catenary structural network showing locations of ceramic links

THE TILING PROBLEM

One could argue that the difference between individual parts should not matter with digital fabrication. This premise only applies if the elements are produced as direct output from digital models. Our intention was to reinvestigate traditional materials using digital fabrication as the tool and die maker, creating molds from which to cast multiples. With these boundary conditions it is imperative to reduce the number if distinct units. By controlling the original tiling pattern before the dynamic simulation we proposed to reduce the number of possible units required to rebuild the catenary network using digital fabrication. We found that no matter what pattern was predefined for the simulation, each edge of the catenary net resolved to a different length. While the structural solution to the catenary form can be resolved using CS-FEM, translating a tiling or chain network to digitally fabricated reproducible components presents several challenges.

Reducing the number and size of the components, the tiling pattern can be tuned according to the structural units being fabricated. Limiting the number of distinct structural units gives the catenary net uniformity while simplifying the fabrication process. Typically, the tiling of a parabolic form of a catenary structure with a single or limited number of tiles or modules would dictate that each piece would have to be appropriately scaled and therefore unique. We hypothesized that the distance from the center points of any three similar tangent spheres when connected creates an equilateral triangle. Similarly, with limited sized spheres, even in aperiodic packing configurations, there exist only a limited number of center-to-center lengths. Further, if the center of each sphere were the center of a chain link, the arms of each individual structural component would remain equal. Perhaps, we thought, this would create a number of repeatable units.

Using our hypothesis as a starting point a tiling pattern was determined using an additional dynamic simulation in Maya. Module sizes were limited to three different radii and rendered as spherical objects and placed within boundaries of the digital cloth. The sphere objects are assigned mass and gravity parameters and the objects are dropped like marbles into the catenary cloth form. Gravity forces the sphere objects into an a-periodic packing configuration tracing the catenary cloth form.

One arm of each structural member spans from the center point of one sphere to the center point of the tangent sphere; the lengths of each arm were limited to the lengths of the corresponding radii of the spheres. Structural units were then generated from the center of each sphere with each arm of the chain extending

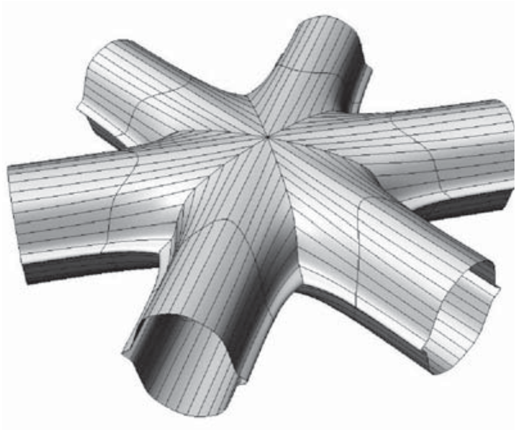


FIGURE 10 NURBS surface of catenary link

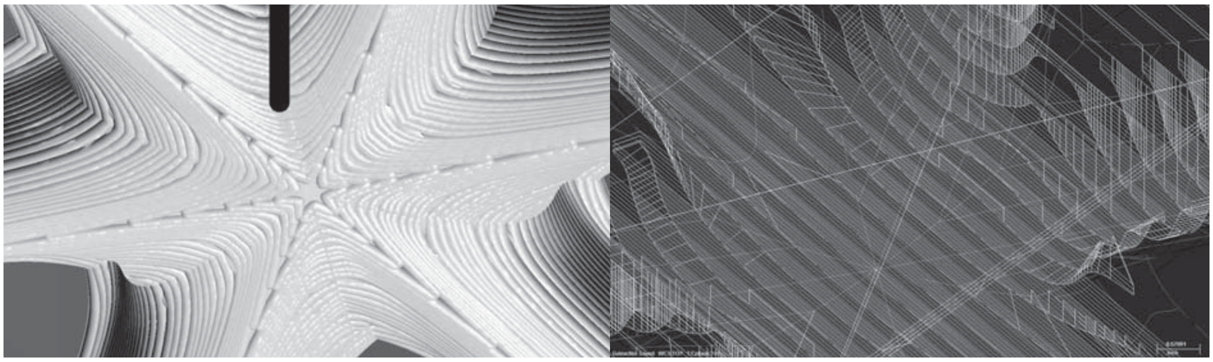
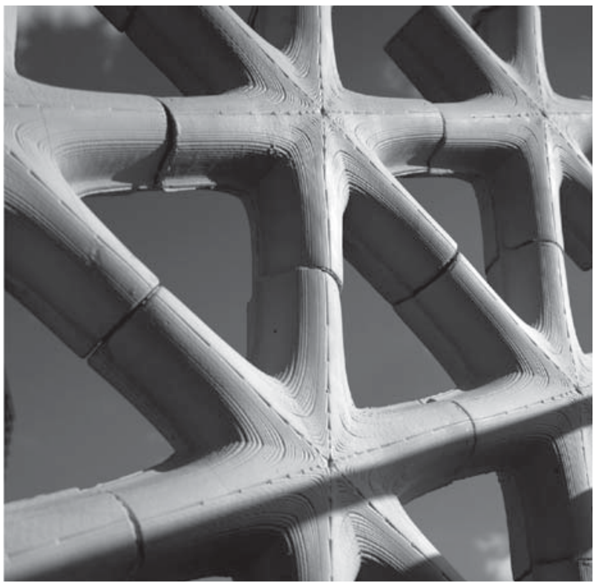


FIGURE 11 Surface tool paths and cut animation in MasterCAM



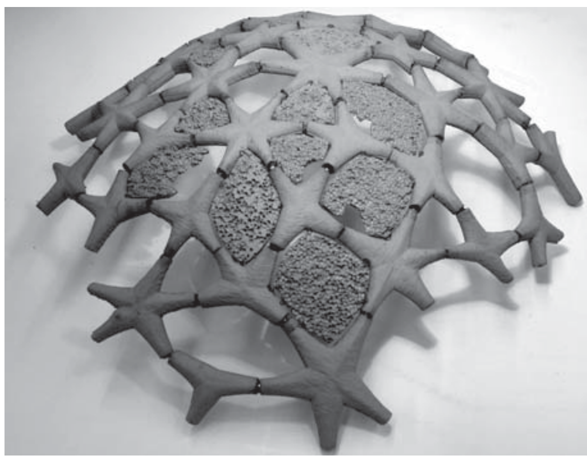


FIGURE 12 (above) Full scale ceramic catenary components, flat network prototype

FIGURE 13 (above right) Seedlings take root on the articulated ceramic surface

FIGURE 14 (right) Slip cast scale model of catenary network towards the center of a tangent sphere. In our initial simulations 13 structural units out of a total 37 had similar geometries. 24 components were required to make the catenary network. Although this reduction is not numerically significant, with further investigation into aperiodic packing configurations we project a significant reduction in the number of required distinct components.

FABRICATING THE CERAMIC CATENARY NETWORK

We have been developing this process as a speculation for form-finding of ceramic catenary networks. Catenary form and associated structural networks generated from dynamic simulations provide an efficient assembly, while the real-time FEM analysis tunes the dimensions of structural ceramic sections.

At the turn of the 20th century the height of building technology utilized hand-crafted ceramic tiles mounted on structural steel framing. There were more than 15 companies in the United States employing thousands of workers making each tile from custom-built molds interpreted from architects' drawings. Now only three such companies remain and two are primarily involved in the historical preservation of old buildings. Yet, the natural process of erosion of the earth's surface produces clay five times faster than we could ever hope to use it. While terracotta has many desirable properties as a building material—durable vitrified (glazed) finishes, thermal mass characteristics (energy efficiency), humidity controlling properties (environmental control), plasticity of form (structural stability)—modern building techniques require an efficient and resilient construction system with a streamlined design and manufacturing process.

To be of significant value a new product for the building industry must be energy efficient, utilize abundant or recyclable materials and must encourage local economic development through appropriate available technologies. Terracotta meets these requirements yet in order to reintroduce architectural ceramics to the construction industry, traditional terracotta forming processes must be reinvented. Slip cast structural ceramics have more structural stability, more surface area for energy dissipation, and better sound absorption through variation in surface texture and depth of relief. Using molds created digitally and producing them with CNC machinery provides a level of precision previously unavailable to the ceramics industry.

Slip-cast ceramic is a multidimensional material. It is comprised principally of silica and alumina and mixed with a deflocculant to decrease viscosity, rendering it capable of being cast. It has high compressive strength, high durability and is very plastic in form; however, it has limited tensile strength. It is these attributes that compel us to reinvestigate ceramics as a material well matched for the geometry of the catenary network, a structural form that acts in pure compression.

Digital fabrication technology offers a unique link between digital design and building construction. Prototypes can be produced, empirically tested, altered and re-produced in a period of time significantly reduced from traditional design and testing methodologies. The advantages of the speed and accuracy of rapid prototyping is the ability to intuitively and empirically investigate both prototypical form and structural principles.

The prototyping process begins with the preparation of the polygonal mesh for output from Maya to Rhino. In Rhino, the surface is converted from a polygon mesh to a NURBS surface. The NURBS surface is exported to MasterCAM. In MasterCAM, tool paths are generated in order to mill the negative of the ceramic shape from a stock material. A Polyurethane rubber positive is cast from negative and used to re-cast a plaster mold. Ceramic casting slip is poured into this plaster mold. The capillary action of the plaster wicks water from the casting slip condensing the larger clay particles against the mold surface. When the desired wall thickness is achieved, the remaining slip is poured out and can be used again. As the slip casting dries further it shrinks away from the mold.

SPECULATIONS

Catenary domes have traditionally been constructed using regular tiles small enough for the mortar to compensate for the curvature. Using digital heuristic processes we have been able to design lightweight ceramic structures made from structural modules proportionally large compared to a typical brick or tile. Developed digitally, the ceramic catenary network achieves similar spans to tradition brick vaulting but can approximate more complex structurally resolved forms.

Mass customization is one possible outcome of our process. However, aperiodic tiling promotes a variability allowing adjustment to differing environmental conditions. Perhaps mass adaptability is a more precise phrase as aperiodic tiling, stochastic models and parametric boundaries offer the possibility of mass variability.

The original Gaudi string models offer a quickness and visceral exactitude of force vectors in catenary networks that still remain unparalleled. With some ease structural sections can be determined and complex networks can, and have been, constructed. Working with digital technology we must keep one eye wary and remember that simulations are only as good as our generating algorithms. Still, the immersive digital environment is seductive for the range of analysis and form generation available through a single screen: dynamic force simulations, structural analysis of complex networks, component morphology and tool path generation working in virtual simultaneity to achieve an effective constructible resolution.

We envision developing the parametric relationship to reduce the amount of distinct tiles, creating inputs for span, site topography, and optimizing geometries for shading. In the future we can imagine developing an output consisting of a list of molds and a key for configuration both parametrically linked to the digital catenary network capable of adjusting in parallel with any adjustments of the catenary form.

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