Apertures – Responsive Architectural Environments

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INTRODUCTION

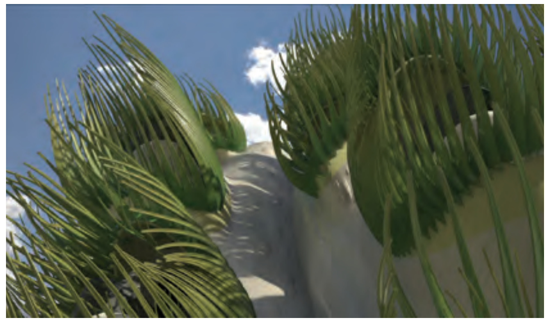
Within the discipline of architecture, the discussion of fields, networks, and smooth transitions has dominated the discourse over the past 15 years. Rooted in the philosophical models of Gilles Deleuze,[1] systems theory, and parametricism,[2] this discussion has influenced many generations of architects. Parametricism promotes a relational ontology in which entities have no autonomous reality and are based on "continuous differentiation"; thus, everything is connected, and everything flows. This position of an architecture rooted in dynamism and deterritorialization is currently being challenged by a radically different approach, giving way to a contemporary design practice working with discrete figures that cannot be entirely understood through their pristine digital relations. This position is one that is obsessed with capturing qualities that would appear to be incongruous by incorporating analog features into a digital design process. The installation *Apertures*, designed for the SCI Arc Gallery, is firmly positioned within this approach.

Apertures are the architectural catalysts for the installation design, being defined as objects within a larger building object that differ from their host in terms of their morphology and performance. They are disruptive features to the overall building mass, but they are able to interact with their environment, producing a symbiotic relationship between nature, building morphologies, and material expression. Apertures have been an ongoing topic in our work. We are

Le Corbusier's Villa Savoye in, France

Daniel Libeskind's Jewish Museum in Berlin, Germany

Aperture design for a housing tower in Lima, Peru



Frank Gehry's Der Neue Zollhof in Duesseldorf, Germany

Enrique Miralles' Scottish Parliament in Scotland, United Kingdom

interested in challenging the notion of an architectural opening as a static object by redefining the DNA of a window, both in terms of its appearance and materiality, as well as its nature as an object in continuous flux, responding to its environment through movement or sound. Unique to this project is the proposal of the building as an organism, challenging how architecture can interface with its users and its environment. The boundary between the human body and architectural object dissolves into an immersive, interactive environment. The project utilizes digital design and fabrication techniques together with synthetic materials and composite construction. The final architectural object is augmented through the integration of sensors and a responsive algorithm to produce a symbiotic relationship between the user and the object, mediated through sound.

HISTORY

On a very basic level, windows make the facade. They determine what the house looks and feels like, while from the inside, they frame the view and bring air and light into the building. Based on their exterior appearance, we can differentiate them into the categories of punched hole windows, glass curtain walls and apertures that are objects protruding from the facade, etc. However, beyond that, windows can also elucidate an architectural idea. They can have a symbolic meaning that has nothing to do with their performance as windows. For example, Jeff Kipnis[3] speaks about the windows of the Jewish museum by Daniel Libeskind as being about a tragedy that occurred in human history and how this was translated into architectural terms. "These windows are not about light, are not about air, and they are not about views as we would normally associate it. They make the thing look, let's say, tortured, fragmented, broken." In Corbusier's manifesto "Five Points of Architecture,"[4] which were most evident in his Villa Savoye, he claims the ribbon window as one of the key features of modern architecture—"the facade can be cut along its entire length to allow all rooms to be lit equally." The ribbon window also does something else; it frames the horizon and denies you from seeing the sky and the ground as you otherwise would through a floor to ceiling window, turning life into a filmstrip. Our approach poses a counterpoint to these two.

We were looking into building upon these two ideas, but simultaneously transforming them in a new approach that deals with the aperture as a "foreign" object inserted into the surface causing the surface to rupture and deform. Our interest in apertures developed while working on a housing tower in Lima, Peru. For us the typology of the housing tower was less defined by the aggregation and organization of units, but actually more defined by fenestration—the window. As the default morphology, the windows in housing projects tended to be ubiquitous ribbon windows. We are convinced that in order to do housing, you must formulate a new approach on how to do windows.

WHAT IS THE DNA OF AN APERTURE?

1. The aperture frame
   - A window frame that is constantly in flux

2. Apertures as autonomous objects
   - They are designed independently from the building massing and exterior surface.
   - They are three-dimensional objects that are inserted into the building mass and can be organized freely and independently of floor slabs.
   - They are transitional objects between inside and outside that can be occupiable.
   - They are directional and focused on surrounding features or follow an external logic.

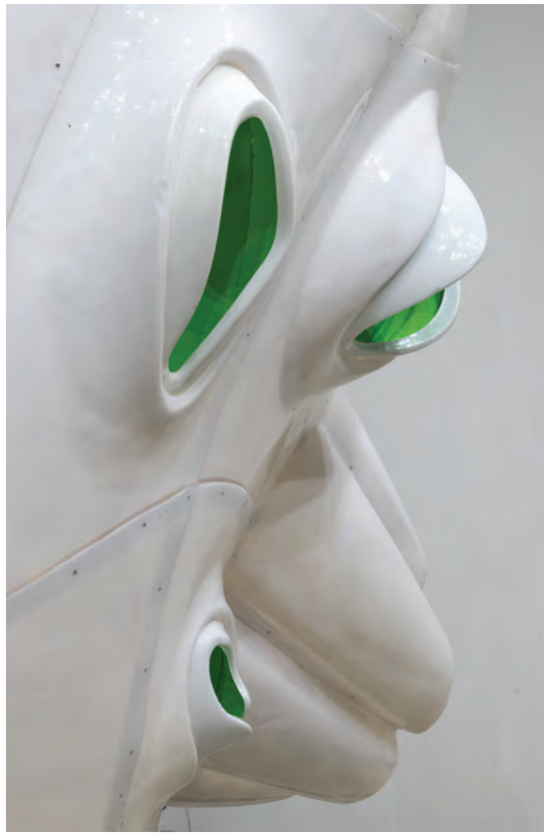
3. Mega-apertures: Multidirectional aggregates
   - Mega apertures form the building mass by aggregating a family of self-similar objects—"flutes"—into a larger whole.
4. Responsive environments
   - Apertures are responsive to the environment through either motion or sound.

1. The aperture frame

Apertures are features of the facade, just as the eyes, mouth, and nose are features of the face. We are accustomed to seeing certain shapes and forms of window frames that we are familiar with and which communicate to us a certain imbedded logic (performative, historic, symbolic, etc). Changing the shape of the window frame, even if ever so slightly, is easily conceived of as uncanny or strange. There are two art pieces that have had great influence on our work on this topic: Bruce Nauman's *Making Faces* from 1968 and Tim Hawkinson's *Emoter* from 2002.

Nauman's work deals with the deformation of facial features, which in themselves can be familiar depending on the degree of distortion, while Hawkinson deals with the dispositioning of parts of facial features through a mechanical apparatus that reconfigures the mouth, eyes, and nose. Although the works of Hawkinson and Nauman are related to one another, the results are dramatically different and show a clear shift from the familiar deforming (Nauman) to the uncanny dispositioning (Hawkinson).

Based on that logic, we started developing a window frame that is in flux and can change its shape over time, rather than having a static frame with a specific form. To be clear, this was not a performance-driven design, like the apertures of the Institute Du Monde Arabe in Paris by Jean Nouvel. Instead, we are interested in the threshold between the familiar and the uncanny that can be



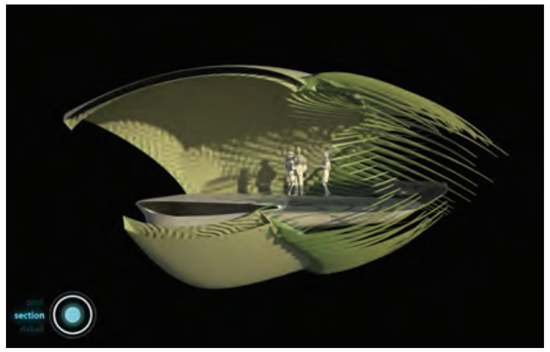
Apertures – view of smaller apertures

produced simply by changing the window frame and introducing motion or sound as a responsive system.

For the housing tower, the window frame was designed with linear extensions along the window frames that create a soft, blurred building edge on the exterior that is constantly in flux. As a material for these components, we propose using advanced silicon composites that combine material properties on a molecular level and allow for the engineering of each component to achieve varying flexibility without the use of mechanical parts. In addition, the new window frames will be coated with thin solar film that will generate electricity for the building.

2. Apertures as autonomous objects

Traditionally, apertures are framed openings that sit flat within the building enclosure as a punched-hole window, or they are defined by the glass curtainwall where the building enclosure acts as the window. More recently, parametrically designed windows have been developed that gradually change their shape and size to seamlessly fit within the continuous flow of surfaces and shapes. In contrast to those precedents, we reconsider apertures as autonomous, three-dimensional objects that are independent from the building enclosure in terms of their morphology and materiality, and that can operate as transitional objects between inside and outside, adding specific features to the overall massing. For example: the roofscape of the Unite D'Habitation by Corbusier uses large cone-shaped apertures both as skylights and as sculptural objects on the roof; the office development Der Neue Zollhof by Frank Gehry deploys rectangular window boxes that are inserted into a curvilinear facade; and the Scottish parliament by Enrique Miralles, which seems like a thesis on apertures as autonomous objects, playfully deploys apertures with different articulation and materiality to give the project its unique character. Greg Lynn describes three contemporary techniques for placing apertures into complex, curved surfaces: "Boolean cuts using multiple figures or surfaces, spline offsets using the curved isoparms of curve networks that define the surface for openings, and facets that fold apertures into surfaces." [5]



Housing Tower in Lima, Peru–overview

There is a certain liberty implied by disengaging the aperture from its host, the building. Apertures begin to act as a spatial device rather than just a cut in the surface or a change of material. Apertures are directional and can be aimed at certain vantage points. Apertures as objects can be designed independently from the logic of the surface and then inserted back into the building. Apertures become a directional and spatial device that can sometimes become occupiable. Apertures can cut and push into floor slabs; they can be deployed independently of floorplates and across multiple building surfaces. This type of aperture produces an architecture that appears to be incongruous.

For the installation *Apertures* in the SCI Arc gallery, we deployed 30+ apertures that are inserted into the smooth surface of the aggregated mass. The apertures are designed following a different rule set then that of their host. When inserted into the surface, they cause deformation and disruption within an otherwise coherent system. Although one would expect that adding these disruptive features would structurally weaken the overall design, it did exactly the opposite. The deformation and local thickening of material through apertures became a structural strategy for how to stiffen particularly weak areas. Color was applied very delicately, and the apertures were painted with a lime green color on the inside, reflecting the color indirectly into the surrounding space and thus emphasizing the interactive sound component embedded within each aperture. Apertures as autonomous objects served not only as transitions between outside and inside, strong drivers to the overall aesthetic, but served a structural purpose without structure being the main purpose.

For the housing tower in Peru, we developed two families of self-similar apertures: an inverted and an extroverted type. The extroverted type is occupiable and protrudes beyond the building envelope, forming balconies and semi-outdoor spaces. The inverted type pushes into the interior and cuts into the floor slab, producing vantage points that are visible from multiple floors. These apertures, as individual autonomous objects, set the aesthetic for the project as a whole, as well as its interaction with the surrounding neighborhood and context.

3. Multidirectional aggregates

Apertures is designed using a technique of aggregating a family of discrete and self similar objects—"flutes"—into a larger whole. Rather than using a Boolean operation where objects are trimmed against one another and merge into a single whole, we instead extended objects past one another and then trimmed them using a set of trimming objects that were later removed. This technique allowed each part to maintain its autonomy rather than merging into a single whole where the parts are no longer readable. On the interior, these trimmed surface edges produce an ordering system of structural ridges that highlights the seams between objects while simultaneously connecting the different apertures and converging into a single interior space with multiple vantage points. The outside does the opposite; it is an extroverted multidirectional object with a strong silhouette that plays off against the flat gallery walls. The two different types of spaces are emphasized through a high-gloss white finish on the outside, and flat white paint on the interior.

4. Responsive environments

The openings respond to their environment through heat sensors and sound. Apertures become a vehicle for interaction, encouraging the observer to physically engage with the work through feedback and adaption between biorhythms of the human body and its environment. The sound component refers to John Cage's observation about the two bodily sounds one might hear in an anechoic chamber that resulted in his famous composition 4'33".[6] The high sound is one's nervous system in operation, and the low sound is the circulation of one's blood. When inside the pavilion or engaging with its aperture, sensors will pick up the biorhythms of the visitor, which are then processed through an algorithm, creating a live sound feedback. The sound simulation was done in collaboration with Vienna Sound Artist Hannes Koecher.

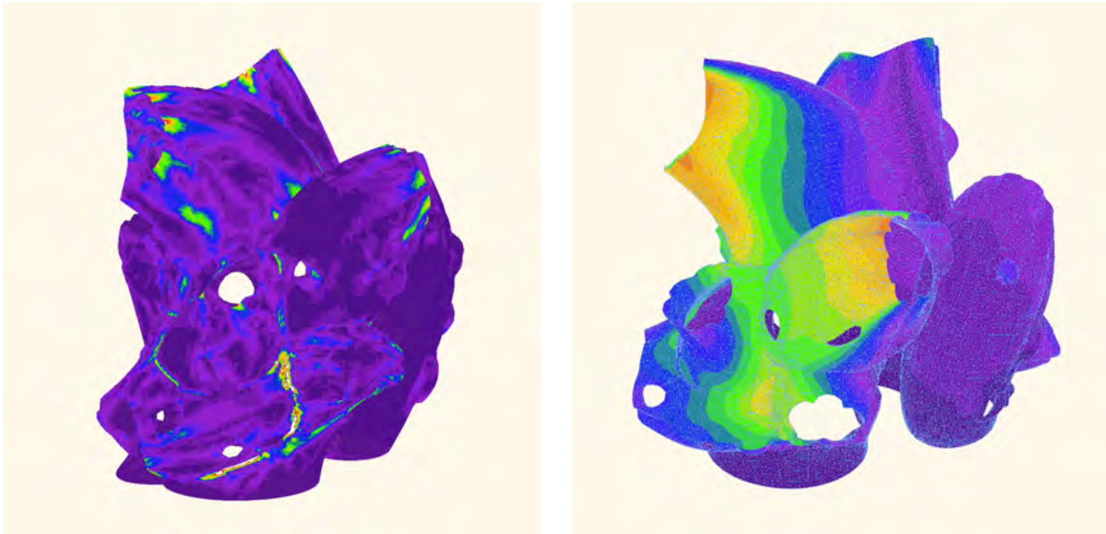
The interactive sound component of the installation was comprised of four primary components: infrared heat sensors; an Arduino microcontroller; a laptop running MaxMSP; and four transducer speakers. Connected over an I2C bus, the 8 MLX90614 infrared heat sensors were embedded into the PETG skin in key locations, where they sensed the body heat of visitors in the space. Using the Arduino microcontroller, this information was collected, numerically remapped, and sent via an RS 232 serial signal to the MaxMSP patch. The serial data was used to drive changes in the sound environment. Four transducer speakers, specifically designed to use the resonant properties of a wood floor, and a subwoofer were installed into the platform of the installation, allowing the sound to be amplified throughout the space without producing the recognizable focal points associated with typical speakers. The effect was an inner body sound ex-

Daniel Libeskind's Jewish Museum in Berlin, Germany

Apertures – interior view

Apertures – view through one of the large apertures responding to body heat through heat sensors and sound feedback

Apertures– responding to body heat through sensors and sound feedback



Images of structural analysis model

perience where one was immersed into a polyphone mixture of low and high frequencies, simulating the sounds produced by one's blood stream and nervous system. As architects, we have been fascinated in finding ways to manifest interaction with a physical object or spatial relationship into a more enveloping experience.

DIGITAL FABRICATION: THE FORM IS THE STRUCTURE – COLLAPSING STRUCTURE AND SURFACE INTO ONE

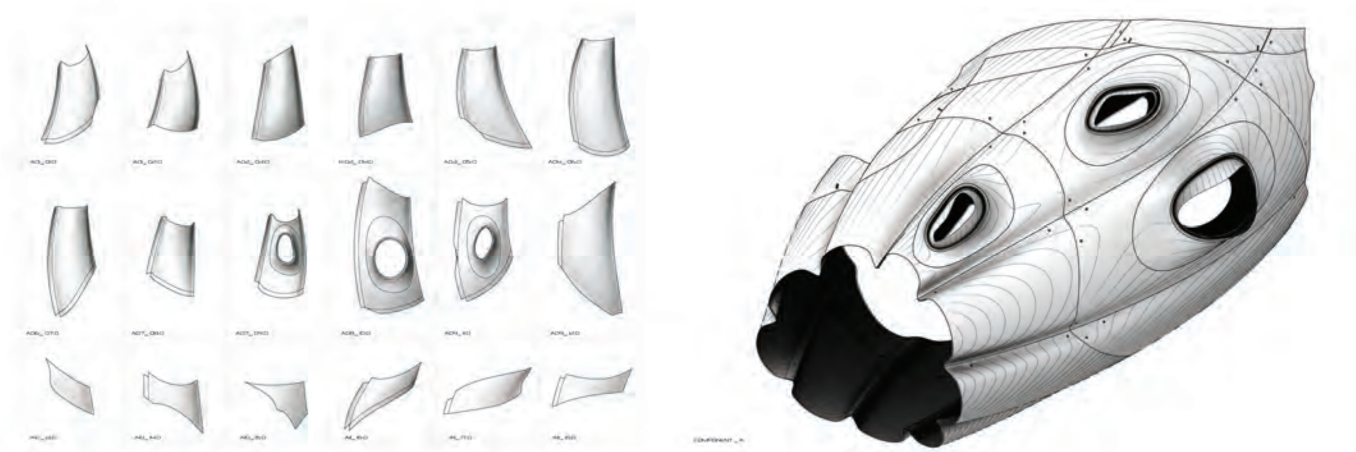
In the typical architectural project, we have adopted construction industry standards of constructing buildings in layers where work has been traditionally divided up by trade. Each of these industries is highly specialized, and coordination between trades has become a highly complex task that results in a high degree of waste in terms of time, resources, and materials.

In contrast, if we look at contemporary industrial manufacturing processes like the automotive industry, the approach is a very different one. The goal there is to reduce the number of parts and to promote the idea of "just-in-time production," originated by Kiichiro Toyota and later perfected by Taiichi Ohno.[7] Ohno was instrumental in developing the way organizations identify waste, with his "Seven Wastes" model which has become core in many academic approaches. These wastes are:

1. Delay, waiting, or time spent in a queue with no value being added
2. Producing more than you need
3. Over processing or undertaking non-value added activity
4. Transportation
5. Unnecessary movement or motion
6. Inventory
7. Production of defects

Today, many industries that deal with composite constructions and hybrids thereof are fabricating things in large components or parts that are specifically engineered for their application. There are very little benefits to working with standard sizes or parts. Everything is custom, and every part is different. In this world, repetition is actually not desirable because repetition has built-in redundancies. When we are dealing with complex geometry and compound surfaces in architecture, we traditionally have gone through a lengthy process of rationalizing the different layers in order to simplify construction and to reduce cost.

When we started to design the installation *Apertures* for the SCI Arc gallery, we initially followed a traditional architectural approach. In collaboration with structural engineer Matthew Melnyk, we designed the finish surface material as a cladding over an egg crate-type of structure. However, it very quickly became apparent that we would have to triple our resources in terms of cost and labor in order to essentially produce the entire installation three separate times—once for the structural core, and the second and third times for the interior and exterior cladding in order to achieve the overall design. Besides that, the interface between the different components became extremely complex, and it reached a point where the design was no longer feasible to construct. Instead, we decided to look at examples from the manufacturing industry and eliminate redundancies by collapsing all these traditional architectural layers into a single layer that can perform multiple tasks, incorporating the structure and finished interior and exterior all into a single entity. The 16-foot-tall, thin-shell structure was designed to rely solely on its extremely thin (1/8") surface as support, requiring no additional structural elements. Structure and surface are collapsed into a single component supported through its shape, creased surfaces, and material strength only. The material performance was critical, and fiber-reinforced plastic (FRP) would have been the ideal material, but it was simply too expensive.



CNC mill file layout per component

We started researching a more cost-effective material that can be formed into any type of geometry, and that is strong enough to build a 16-foot-tall structure. We ended up choosing a material that is widely used to make water bottles, a thermoplastic polymer resin, which comes in sheets and is extremely soft as a flat sheet; however, when formed into a compound curved shape, it becomes fairly rigid. In addition to this aggregated mass of double-curved thermoplastic, creasing of the surfaces was added for both aesthetic and performative reasons. The creases further defamiliarize the individual objects by introducing features that were not part of the initial mass. Unlike a conventional shell structure that generally takes the form of a smooth or continuous surface, *Apertures* is composed of a cluster of interlocking shell parts. Each shell "part" is further broken down into many unique heat-formed panels made of 1/8" thick PETG plastic that is, by structural engineering standards, a soft or low modulus material when compared to more common wood or fiberglass.

Transforming this very thin material into a rigid shell was accomplished though a number of ways. The VacuForm process of fabrication allowed us to produce panels with double curvature, which greatly improves stiffness in bending. Additional stiffness was derived by adding folds. The cylindrical shape of the funnels themselves provided even more stiffening. Still, the individual parts were found to be very flexible. Fortunately, it was the global geometry that provided a solution. Once the individual pieces are assembled together and attached to the base platform, they interlock in such a way as to produce a stiff and stable shell system.

The complexity of the interlocking shells proved to be a challenge. In collaboration with our structural engineer Matt Melnyk, we used a variety of methods to understand the system and evaluate how it was working, including physical modeling, computer models, and computer simulation. Finite element analysis was used to test stability and to verify that the forces in the shell were within allowable limits. Due to the softness in the material, even minimal force could cause the piece to drift latterly, although the interlocking shells held together very well and remained taut. The resulting shell weighs approximately 800 lbs. and appears to stand effortlessly.

MOLD MAKING – CNC MILLING – POLYURETHANE FOAM

The design of *Apertures* was thoroughly vetted in the computer; we looked at each panel joint, each overlap, and a general idea of where each rivet would be placed in the final design. The installation was then translated and confirmed with a physical model, and translated again and broken into the 233 individual plastic panels, all different from one another and varying in size and shape. In order to make each panel, we had to CNC mill 233 molds out of polyurethane foam. Polyurethane foam is widely used in the aerospace industry for mold-making and soft tooling because of its precision and pressure and heat resistance. We also tested other types of foam of lower quality and tried to compensate for the lack of heat resistance with different types of coatings, but ultimately, we could never get a smooth finish off the plastic surface because of the deformation of the foam that occurred through heat and pressure during the heat forming process. The foam we used was 4 lb. polyurethane foam that is just sufficiently dense enough for a one-time heat forming process.

CNC milling

Polyurethane foam mold on the heat forming table

Heat forming of 1/8" polymer resin over the grey protective layer

SCI-Arc student cutting the heat formed PETG panels

Drawing of the nine components that make up Apertures

For the next two and a half months, SCI-Arc students CNC milled the 233 molds out of polyurethane foam on 4'x8' mill bed. We ended up using an entire shipping container full of polyurethane foam to produce all the molds.

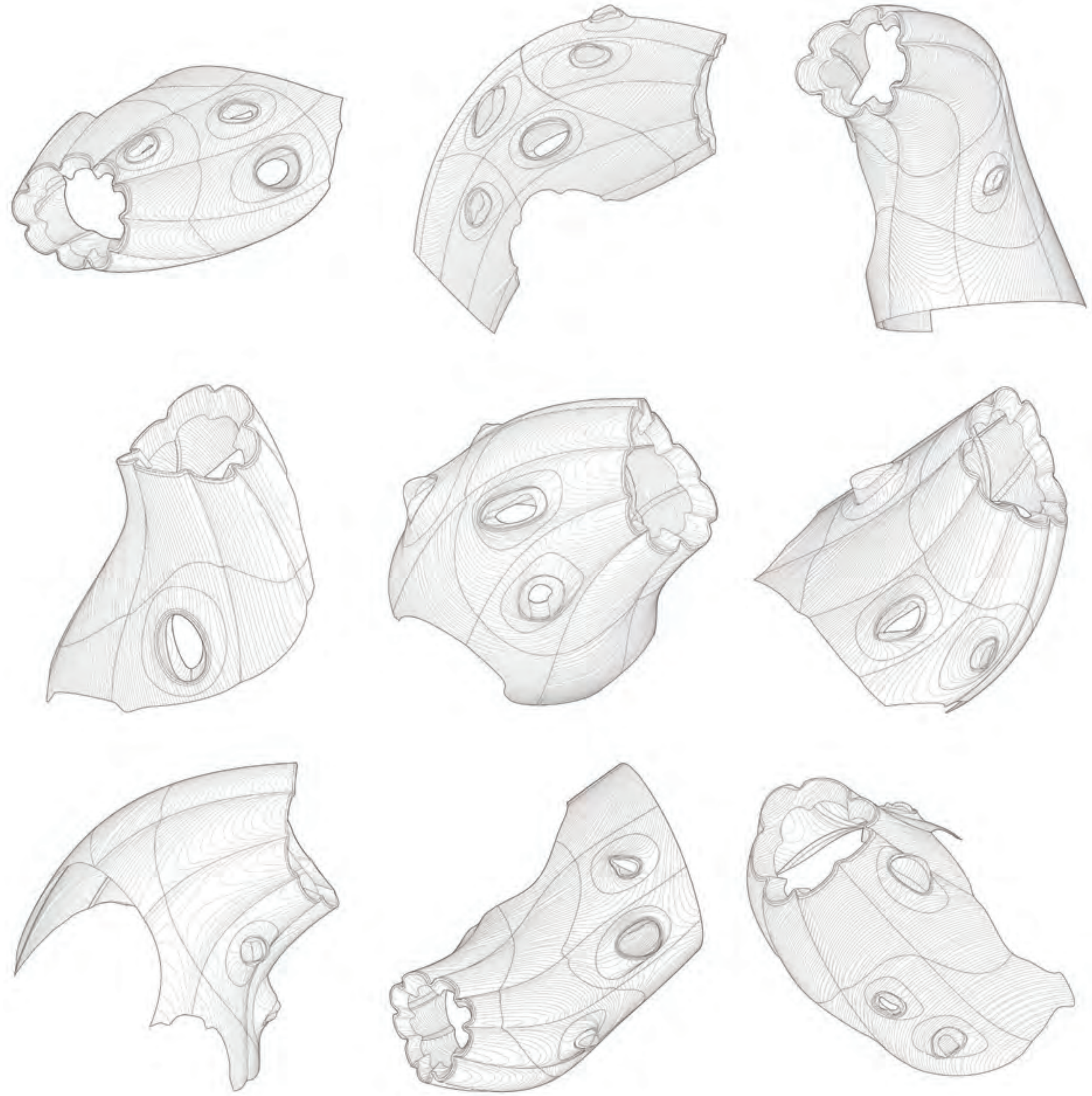
HEAT FORMING

The heat forming was done on an industrial size 5'x10' vacuum forming machine. Each mold was first pulled with a thin layer of grey styrene as a protection sheet and to be able to facilitate the separation of the finished material from the mold. The next and final pull was done using 1/8" thick sheets of thermoplastic polymer resin. Each sheet was then cut out, labeled, and painted with a flat white color from the back side, which gave the glossy finish to the exterior. The finished panels were then delivered to the gallery.

ASSEMBLY – SCAFFOLDING

The 233 panels were assembled into nine large components. Panels were joined with pop rivets. Each component was then assembled and joined with one another to form one large object. In order to keep tolerances very tight, we constructed wood scaffolding out of three horizontal rings that were CNC milled. The scaffolding provided a control mechanism for the tolerances and temporary support as the 16' tall structure was erected. The individual components were extremely soft by themselves and only achieved their final stiffness after all nine components were joined with one another. Installation was completed within one week.

In conclusion, the SCI-Arc gallery installation *Apertures* was a successful proof-of-concept mock-up that investigates apertures as a responsive architectural element and utilizes digital design and fabrication tools to do so.



ENDNOTES

1. Gilles Deleuze, *Repetition and Difference*, trans. Paul Patton (Paris: Presse Universitaires de France, 1994).

2. For more on parametricism, see: Patrik Schumacher's *Adaptive Ecologies: Correlated Systems of Living* (London: Architectural Association Publications, 2013) and The Autopoiesis of Architecture: A New Framework for Architecture (London: Wiley, 2011).

3. Jeff Kipnis, "Windows: Outline of Architecture" (lecture at Ohio State University, November 18, 2008).

4. Le Corbusier, *Towards a New Architecture* (Original: Vers une architecture, 1923) (New York: Dover, 1985).

5. Greg Lynn, "Apertures," in *Greg Lynn Form* (New York: Rizzoli, 2008).

6. 4'33" is a composition by American composer John Cage in which the performer is not to play their instruments for four minutes thirty-three seconds. The piece purports to consist of the sounds of the environment that the listeners hear while it is performed.

Apertures – view through one of the large apertures responding to body heat through heat sensors and sound feedback

Installation at the SCI-Arc gallery

SCI-Arc students lifting one of the nine components into place

7. Taiichi Ohno, *Toyota Production System: Beyond Large-Scale Production* (London: Productivity Press, 1988).

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IMAGE CREDITS

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