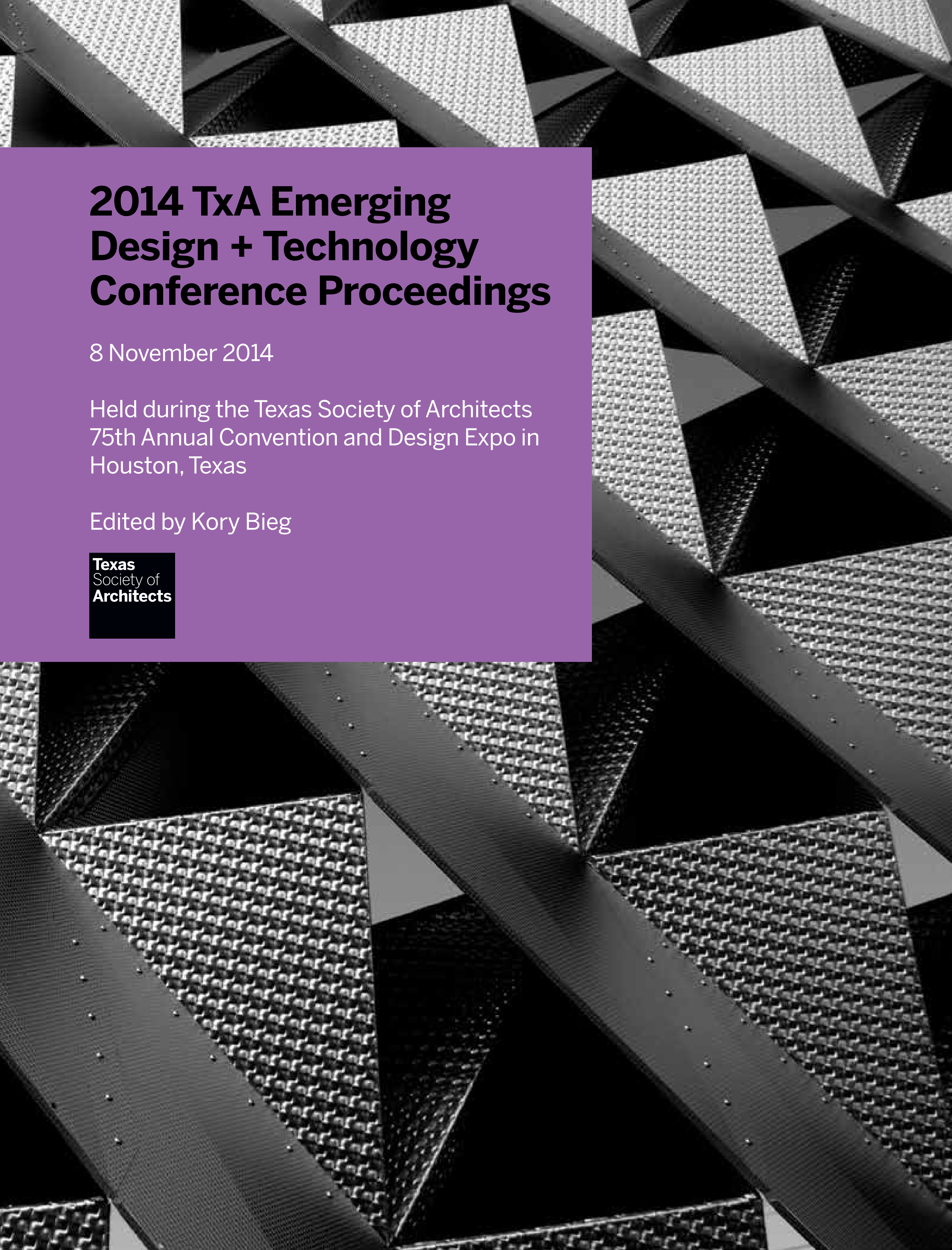

2014 TxA Emerging Design + Technology Conference Proceedings

8 November 2014

Held during the Texas Society of Architects 75th Annual Convention and Design Expo in Houston, Texas

Edited by Kory Bieg

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Introduction: The Substance of Material

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This year's TxA Emerging Design + Technology conference, now in its second year, took an unexpected turn. Papers were less about the development of new technology and more about expanding the capabilities of current technologies, including those that are still at the forefront of the field. By delving deeper into CNC machining, 3d printing, and robotics, architects are mining current technologies for new aesthetic, formal, and performative opportunities.

Until recently, the use of these tools had been geared toward the realization of projects with a formal complexity previously inconceivable. The ability to produce many parts with each part varying from the other has allowed experimental architects to design incredibly rich and elaborate structures. These projects have pushed design aesthetics into altogether new territories. What emerged were projects that embraced complexity—projects in which the whole added up to something far greater than the parts themselves.

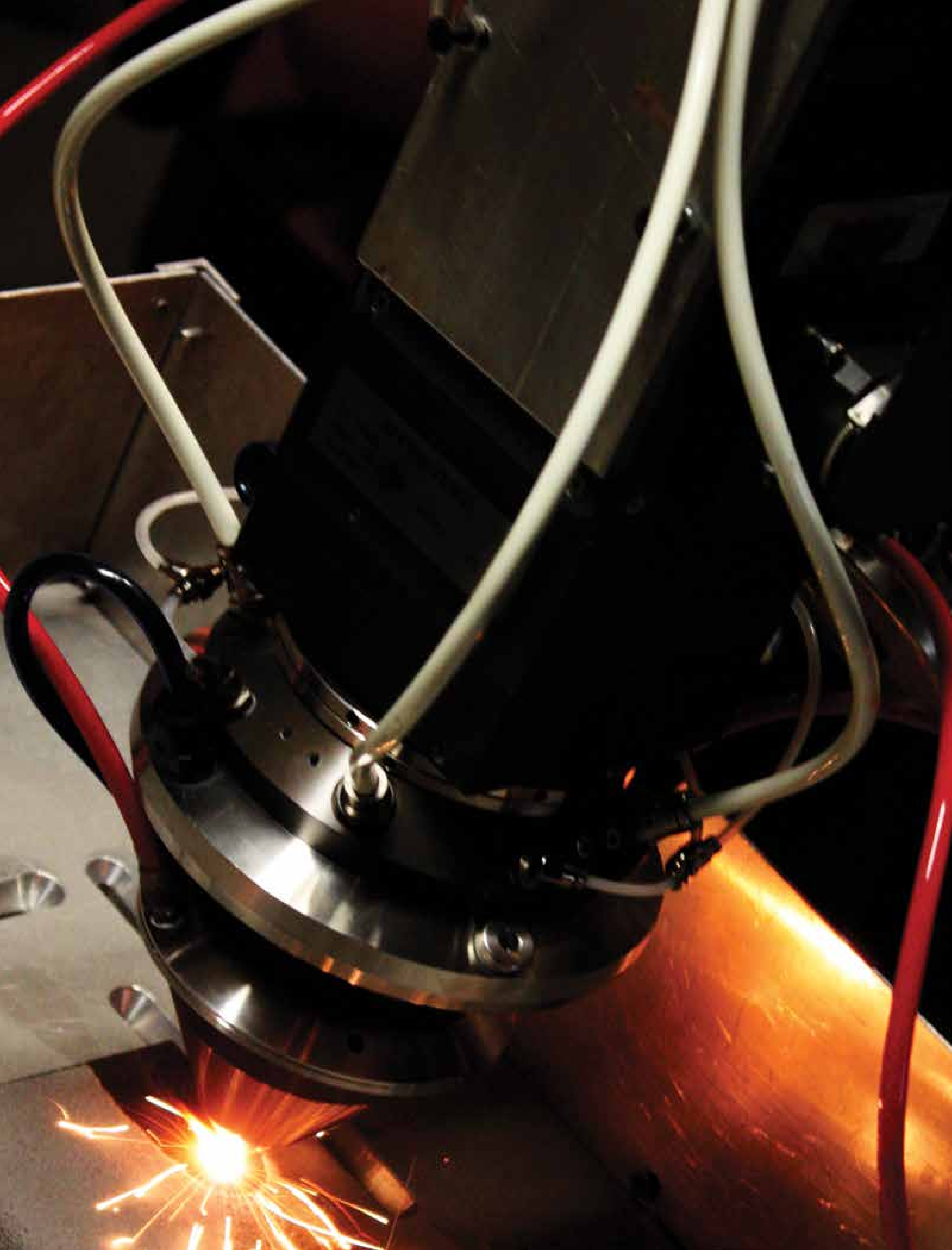
But what was left aside, until now, was the *what* with which we were working—the material. Material had been treated as stock, in most cases as a uniform block that could be carved and shaped to match some digitally modeled form. Material was selected for its strength and malleability in whatever combination would best realize the form. It was rare to use multiple materials in concert with each other for form making, except by assemblage and mechanical connectivity.

We are now moving into a new territory, one in which the word *material* is perhaps not best suited for the next stage of CNC technology. *Material* suggests a discrete thing, something with limited bounds, a monolith. Perhaps *substance* better describes where we are headed. Substance speaks of combination, mixture, and variable properties. *Substance* is not final; it is not discrete; it's in a constant state of change, or at least potential change.

By using CNC technologies to manipulate and give form to substance, a wide range of new combinatorial projects are being realized. We are starting to tap directly into material properties to expose a deeper knowledge of specific materials—not just, for example, that wood has grain, but precisely where the grain is and how the location of grain can be fed directly back into CNC path tooling to influence how the material is cut. As data is fed back in real time to the tool, the tool's path can be redirected to take better advantage of the exact composition of a particular stock. We are finally able to identify material differences not just between different materials, but within a piece of material itself.

In his essay "Material Evolvability and Variability," Manuel Delanda notes that Eskimos have 29 words for snow: "There are 29 different combinations of the solid and the liquid, which give very different kinds of snow. When a material is as important as snow is for Eskimos, synonyms begin to accumulate ... [and] begin taking on subtle shades of meaning marking subtle differences in their references. In other words, material variability is not dependent on or created by linguistic variability."* The potential for direct feedback between each material's highly unique and particular properties and the CNC tool being used to transform it was always there, but until recently we haven't had the capacity to directly engage it. By doing so, we are beginning to create new forms that transcend previous limits to aesthetic and formal complexity while engaging performance and function is an altogether novel way. We are starting to connect our making process to our thought process. Emerging technology is not just a means to an end, but has become a new tool for generating ideas.

* Manuel Delanda, "Material Evolvability and Variability," in *The Architecture of Variation,* ed. Lars Spuybroek (New York: Thames & Hudson, 2009), 11.



Additive Manufacturing, Abstract Assemblage, and Material Agencies

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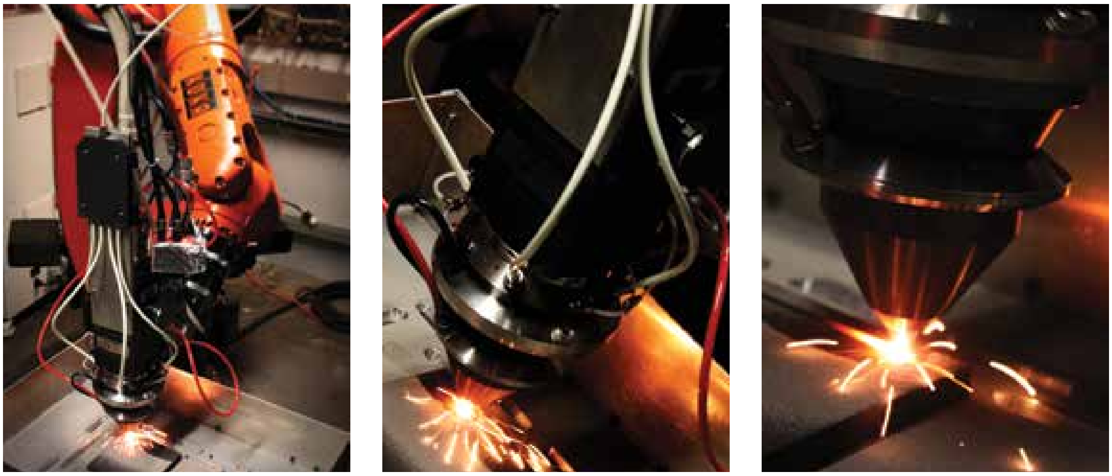
AN OVERVIEW OF ADDITIVE MANUFACTURING IN METALS

Within the last decade, a variety of systems for the additive manufacturing of metals have been introduced to the market. These can be loosely characterized according to the material deposition process, heat source used for fusing, and physical constraints of fabrication. The majority of these show little deviation from the first patents filed by Pierre Ciraud (1972) and Ross F. Housholder, and are fundamentally equivalent to selective laser sintering, or SLS (Beaman 1997). These 3-axis systems rely on a bed of metallic powder to support each subsequent layer as a heat source selectively fuses or welds the metal powder to the previously fused layers. After sintering, the build chamber lowers, and a new layer of fine metallic powder is applied. Like most rapid prototyping technologies, this process allows for design complexity unachievable through conventional manufacturing processes.

The second classification of additive manufacturing systems is differentiated according to the way material is delivered. These direct metal deposition, or DMD, systems deposit material precisely where needed and range from three to five axes. Since they fuse metal directly to the substrate material previously applied, they are less dependent on support material and offer significant decreases in build time. Among the most robust of these is the 5-axis LaserTec65, developed by the CNC machining systems manufacturer DMG-Mori. This 5-axis system is based on their existing machining systems design, features 5-axis, additive/subtractive operations, and offers a notably larger build area than most powder supported machines. This approach is commonly referred to as hybrid manufacturing. In general, additive manufacturing of metals is restricted to near-net shape fabrication. This is partially attributed to the resulting surface roughness and tolerances associated with mated surfaces. Because of this, components must go through post-processing before completing their production time. Utilizing hybrid manufacturing minimizes coordination between these processes and allows for additional complexity since both processes can alternate during fabrication.

A third class of systems extends from previous research and development within Southern Methodist University's Research Center for Advanced Manufac-

Figure 1: Robotic work-cell for research based on free-form direct metal laser sintering (DMLS). Features include coaxial powder delivery, 4kW fiber laser, and high-speed monitoring CCD. Dual powder hoppers supply powder at numerically controlled rates for in-line control of material composition.



turing and builds upon the patents of Dr. Radovan Kovacevic (2006). This system is similar to the previous classification in regards to material delivery, but utilizes a 6-axis robotic arm to control the deposition paths (and in some cases feature an additional tilt-rotary build platform manipulator). Because this system is not fully enclosed or self-contained, the build area is restricted only by the robot's range of reach and allows much larger structures than proprietary machines. Additional axes allow for greater degrees of freedom and flexibility for medial path planning (Dwivedi et al. 2006). Medial path planning is not limited to slicing along the z-axis. In this case, sections are sliced and paths are organized along the medial axis of predominant features within the component's geometry (Dwivedi et al. 2007). Paths may also be organized to move freely along complex surfaces relative to perpendicular normals. Path planning for these systems becomes increasingly complex, but allows advantages in regards to topological complexity without the aid of sacrificial support material.

While there has been considerable improvement to the control of process parameters, dimensional tolerances, and resulting mechanical properties, the application of additive manufacturing in metals to architectural research has seen little attention compared to the enthusiasm demonstrated by a larger body of architectural research based additive manufacturing in other materials (Warton et al. 2014). Among the few cases published is the work of Joris Laarman and IAAC's MX3D-Metal,[1] which draws some similarity to the robotic processes noted previously. This project presents a novel approach to path planning, but the wire-fed MIG welder proves insufficient for mechanical properties and controlled tolerances required for research leading to structural implementation. The Multithread collection by Clemens Weisshaar and Reed Kram[2] exhibited at the Istanbul Design Biennial 2012 serves as a potential precedent for metal structures that utilize 3D printed forms. These forms are then cast in steel using a lost-wax process (Kram et al. 2012). Similarly, Matt Hutchinson[3] of PATH investigates the coupling of off-the-shelf standardized stock with parametrically differentiated elements. A recent example investigating an architectural application of additively manufactured metals was released in June 2014. Arup and Salomé Galjaard[4] produced a 14 cm scaled connection prototype composed of maraging steel. This particular project begins to investigate topological complexities, whereas the previous projects gesture more toward mass differentiation. In each of these three cases, the project promotes the effective application of AM and metals to structural connecting members, as well as synthesis between structural performance and aesthetics. Aside from Laarman, these projects operate in the more conventional file-to-fabricator workflow and rely on the proprietary powder supported machines with a size limitation typically under a cubic foot.

Despite this apparent limitation in size, several independent contractors and research institutions have developed technologies where a modest architectural scaled execution is feasible. Researchers at Northwestern Polytechnical University of China have demonstrated that additive manufacturing is effective for metal components as large as 3.1 meters and have validated their process through rigorous mechanical testing (Huang et al. 2014). Their test case, LSF wing spar cap strips, will be fabricated in TC4 (Ti-6Al-4V) alloy and is targeted for production on the Comac C919 by 2018.[5] Similarly, Sciaky Inc., a subcontractor of Lockheed Martin, markets its ability to produce parts with dimensions up to 19' x 4' x 4'.[6] It also claims to build up material at speeds approaching 250 cubic inches or 40 pounds per hour, significantly increasing the production speed achieved by the smaller powder supported systems.

EXPERIMENTAL SETUP

Building upon these various processes, a work cell comprised of a 6-axis Kuka KR-60 robotic arm, a 4 kW fiber laser, and a co-axial powder delivery system for the direct deposition of fine metallic powders has been assembled in the Research Center for Advanced Manufacturing (fig. 1). This work cell implements freeform sintering of metallic powder and is planned for extended capacity to produce functionally graded structural components comprised of heterogeneous alloys and coordinated subtractive milling. Multiple powder feeders allow for controlled composition and support the production of functionally graded components. The composition can be graded to achieve both aesthetic and performance-driven criteria, as well as to minimize cost by concentrating more expensive materials precisely where they are desired. The implementation of heterogeneous powder delivery requires calibrated powder control and monitoring (Mei et al. 2002). Commercially available powder delivery systems have been designed for purposes other than additive manufacturing. The difficulty with appropriating these systems arrives when precise control of very small amounts of material is needed. Most of the current systems are designed for feed rates higher than those required for powder-fed direct metal deposition. Within our center, research and development is underway to improve upon these systems and offer viable low-volume feed rates with precise monitoring and control for improved process stability, mechanical properties, and powder catchment efficiency (Liu et al. 2014). The experimentations presented here maintain feed rates that are at approximately .5 grams/sec or 4 pounds/hr. This is notably slower than Sciaky's claims, but is considered an acceptable trade-off for exploration of heterogeneous composition. This rate is nevertheless significantly faster than the differentiated lattice and node assembly prototypes produced using the powder supported ARCAM A2 Electron Beam Melting system shown in Figure 2.

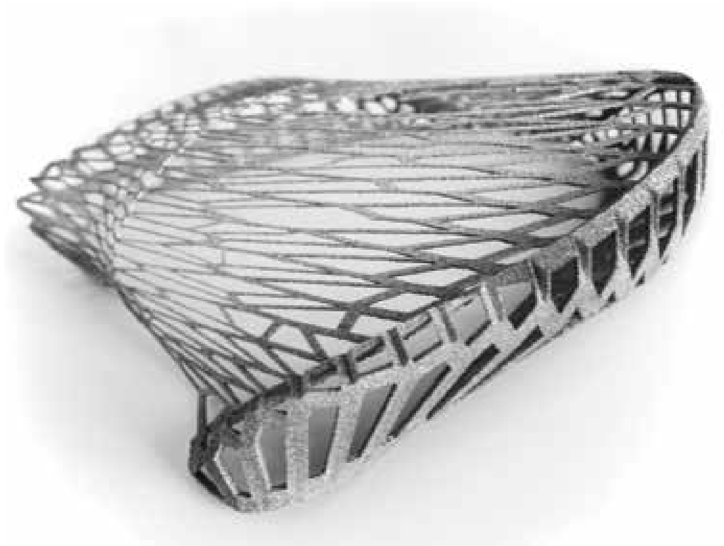


Figure 2: Procedural lattice structures featuring variability within each element. a) This prototype was developed as a hypothetical design for a highly articulated structure where element design is informed by discrete loading criteria. b) Assembly prototype comprised of seven unique components. Automated design-to-fabrication enables the production of mass customized assemblies.

THEORETICAL FRAMEWORK

The research methodology presented balances objectives within various disciplines of design research. Investigations explore a range of criteria, including fabrication constraints and mechanical and structural performance, as well as the aesthetic and formal consequences arising from the implementation of nascent technologies. This research methodology is coupled with an acknowledgement that form arrives into being at least partially from productive participation with material properties and the means of making as a mode of technê. Our view of technê can be characterized through a dynamic assemblage of interdependent material and machinic agencies that act upon the various aspects of a design artifact's revealing.

The notion of technê was essential to Aristotle's view of aesthetics and its role in poiesis or 'bringing into being'. For him, technê was centered on an informed and knowledgeable maker and the mastery of one's productive activity. "Technê involves a true alignment of the axis of potential/realization in human productive activity: it is concerned with bringing into being, by intelligible and knowledgeable means, objects whose existence depends on their maker" (Halliwell 1998). This traditional conception of artisan and the mastery of craftsmen is however distinct with regard to the proposed methodology and aligns itself more closely to a notion presented by Heidegger (1977). In his essay "The Question Concerning Technology," we are provided with an example of a silver chalice that owes its revealing to shared dependency between the silver as matter, the chalice as a signified object, and the silversmith's gathering together of acting elements. Barbara Bolt (2007) describes this shared dependency as "a play between-the understandings that we bring to the situation and the intelligence of our tools and materials" and goes on to say, "This relation is not a relation of mastery but one of co-emergence". The dependencies described offer a clear route into engagement with these elements of agency and reorient the focus away from a strictly defined or clearly articulated outcome. Furthermore, this emphasis on interdependency gives way to the notion of technê as a participatory assemblage. According to Jane Bennett's (2010) analysis of Delueze and Guattari, "Assemblages are ad hoc groupings of diverse elements exhibiting emergent properties." She continues: "Each member and proto-member of the assemblage has a certain vital force, but there is also an effectivity proper to the grouping as such, an agency of the assemblage."

Together, these ideas suggest the adoption of an approach directed toward the guiding forces within this abstract assemblage. The methodology proposed is signified through its participation with the material artifact as well as the apparatus employed to achieve an end and engages rigorously with the methods and mechanisms for making. If technê illustrates an alignment of potential with one's productive action, further engagement amplifies the domain of realization. Proactive commitments to the composition of material, mechanisms for production, and customization of design tools encourage dynamism within the manifold of possible outcomes.

MULTI-SCALED PERFORMATIVE EXPRESSION

The notion that materiality has fundamental formal consequences was demonstrated within architectural theory and discourse as early as the nineteenth-century writings of Eugène Viollet-le-Duc. He clearly articulated enthusiasm for novel materials and believed that proactive involvement with industrial practices and methods of manufacture would enable the production of "new forms" (Hearn 1990). In response to the advancements of iron in his time, he writes: "Let us study its properties, and frankly utilize them, with that sound judgment that the true artists of every age have brought to bear upon their works." These beliefs manifest themselves within his work through expressions of structure, spatial organization, and ornamentation. Since then, refinement of metallurgical practices leading from wrought iron though ultra-high-strength steel have ushered in seminal contributions to the design and engineering of lightweight structures from Buckminster Fuller, Chuck Hoberman, Frei Otto, and Robert Le Ricolais. The high density, fracture toughness, and relative strength-to-weight ratios have made alloys a driving force for such explorations and have contributed greatly to the catalog of seeming weightlessness and transparency of structure. Additive processes for fabricating metal systems additionally offer a new era of design potential in regards to lightweight structures. In order to capitalize on this potential, intelligent design techniques must be employed.

A prototypical design approach has been adopted based on the form-finding methods of Frei Otto. The development of spring equilibrium algorithms loosely based on his tensioned spring models for optimized branching systems serve as the basis for global as well as nested organizations of material and spatial differentiation. Spring behavior modeled after Hooke's law is embedded within the individual elements of recursively generated branching systems. This provides the exploration of novel configurations and parametric control of both the organizational and behavioral forces driving the

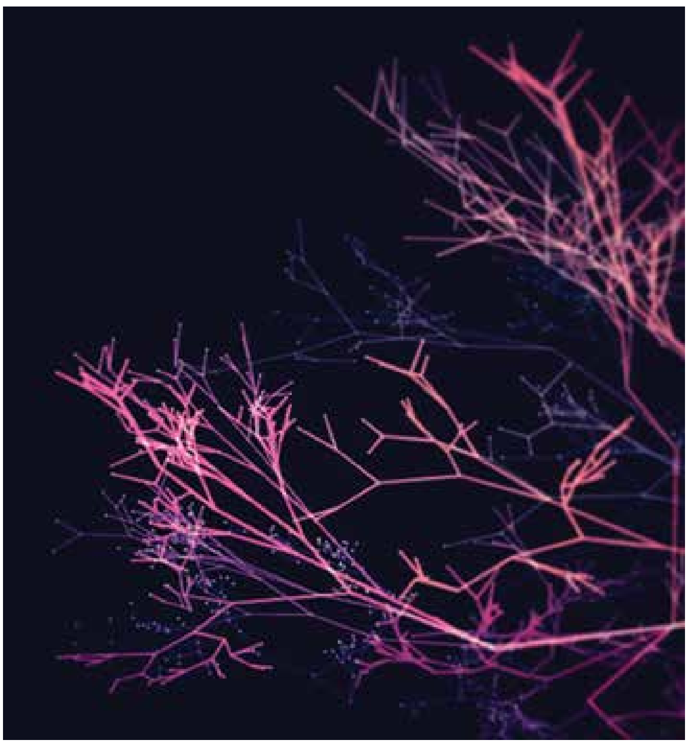


Figure 3: Examples of recursive branching structure with associative node relations. These relations allow for spring- and physics-based behaviors and structural matrix analysis.
a) Color and thickness parameters can be linked to various modes of analysis for design feedback before applying mesh routines. b) Branching structures after spring equilibrium is obtained.

outcome. Initial conditions are set to determine branching depth, branching factor, and leaf factor (fig. 3). Stable relations between elements and nodes allow the system to relax into a state of equilibrium spanning between predetermined points of fixity. The organization of element relations provides additional benefit in regards to analysis. Once the system reaches equilibrium, structural matrix analysis using the finite elements method (FEM) is applied to determine local stresses and axial forces within the system. Reactions and nodal displacement can also be determined based on loading cases unique from the generative forces initially applied. The FEM feedback can then be used to inform cross sectional area and design constraints for each element and node component within the system. Once these parameters are determined, a meshing algorithm is applied to establish the volumetric boundary representation (fig. 4). Matrix analysis at this low-resolution stage provides an efficient approach for complex structures comprised of an abundance of dissimilar elements. Coordination of elements and node relations for large systems of this type can be tedious and prone to error. Through integration of algorithmic form-finding and matrix analysis, a multiplicity of design options can be explored with higher degrees of structural feasibility while alleviating error associated with coordinating these processes manually.

The abstract assemblage of material, means of making, and methods of design contribute to an endeavor for multi-scaled structural articulation. Together, this ensemble promotes and enables a precise and calibrated engagement at scales ranging through the organization of material composition, discrete connections, elements of assembly, and their diverse spatial distribution. The expression of complexity and synthesis of performance can traverse the full range of architectural scales while satisfying objectives to achieve visual nuance, intricacy, and delicate lightness. These optimizations are not entirely centered on functionality of structure; rather, they respond to desires for visual levity and animated suspension of multi-scaled fields of density. Stress accumulation and buckling resistance within these novel structures is essential, and design features to satisfy both visual and performance criteria must be developed. An essential feature of additive manufacturing processes is the ability to fabricate complex topologies with internal voids and stiffening members (fig. 5). The morphology of hollow bone structures found among birds represents an effective model for lightweight assemblies. The thin exterior wall in these structures is stiffened by an internal network of struts, and reduces the overall mass associated with its skeletal system. Unlike extrusion or built-up plate assemblies, similar features can be embedded within additively manufactured thin-wall cross sections without added complication during the fabrication process.

Prototypes testing this concept were developed starting from a solid hypothetical node subjected to

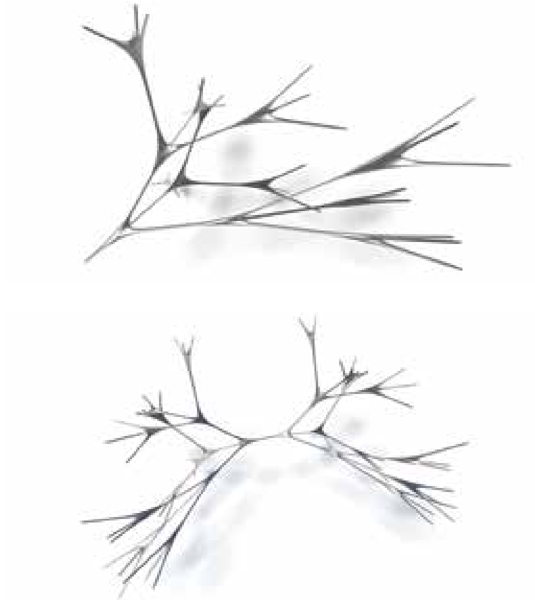


Figure 4: Results from cage-based meshing algorithm. Algorithm accepts arbitrary vectors with shared node relations as input and requires numeric input for parameters defining the cross section's geometry.

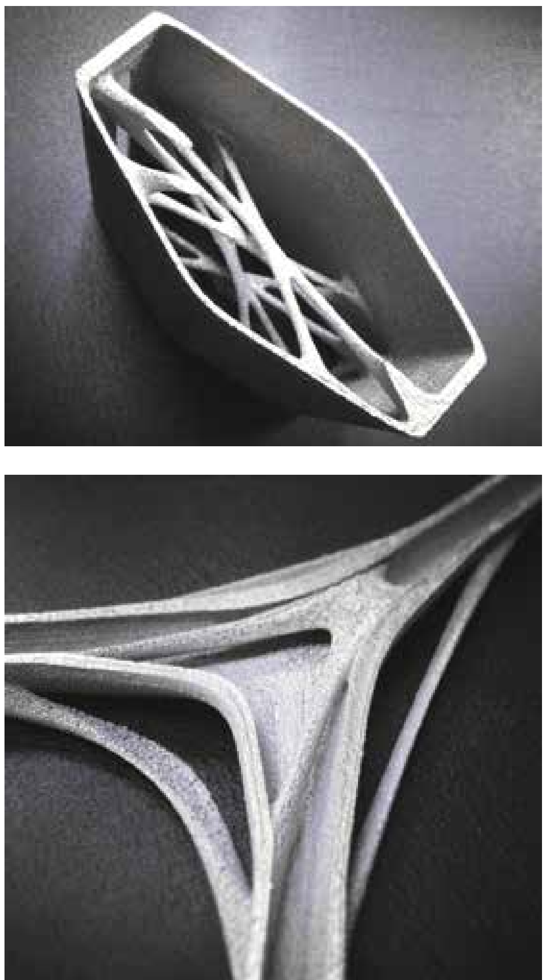


Figure 5: Cross section prototypes revealing internal lattice structures modeled after avian bone morphology. a) This 2" x 4" tube section has a principle wall thickness of 1/16". b) Variable wall thickness based on results from multiple iterations of FEM analysis and design.

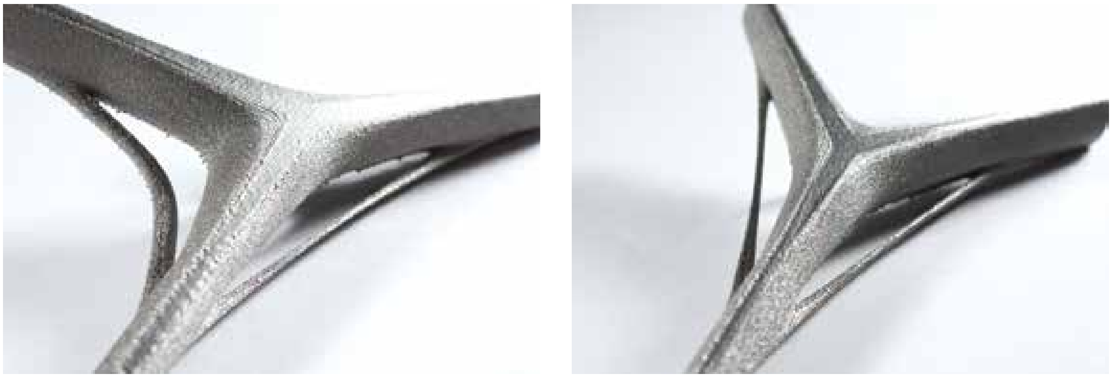


Figure 6: Titanium Y-branch prototype produced using electron-beam melting (EBM).

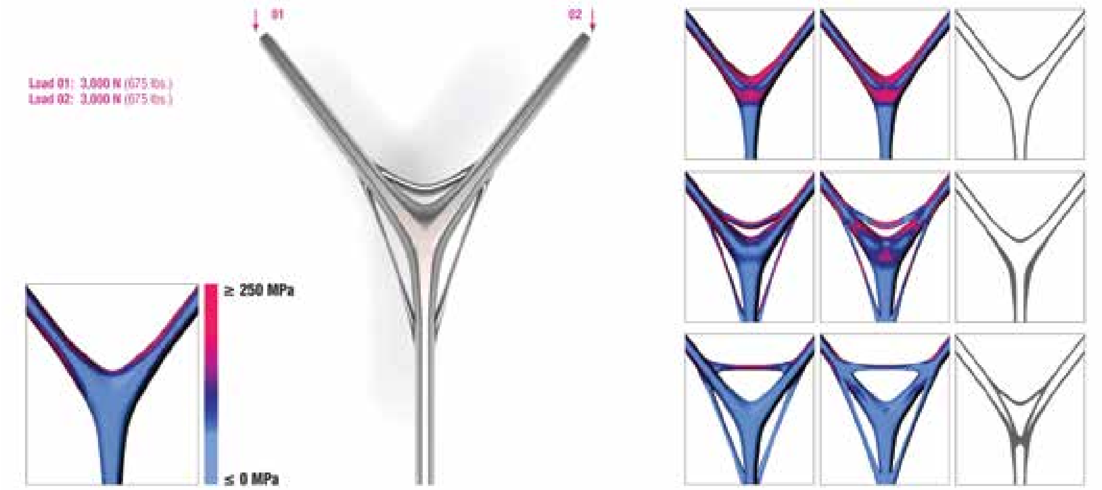


Figure 7: Stress accumulation observed in solid and uniform wall thickness designs inform subsequent iterations incorporating variable thickness and stiffening members.

FEM analysis (fig. 6). Resulting stress concentrations were compared between both solid and hollow versions. Thickness variations and reinforcing struts were incorporated in response to concentration patterns noted in the resulting gradient maps. The hypothetical load case consists of two 3,000 N forces and produced a maximum stress value of 315.57 MPa. The loading criteria were satisfied with a 34.6% reduction in mass. Maximum local displacement was reduced from 3.88 mm to 1.92 mm (fig. 7).

FUNCTIONAL INTEGRATION AND DESIGN FEATURES

In addition to apparent lightness stemming from optimization of structural performance, integration of building infrastructure provides opportunities to minimize visual clutter. The complexity achievable with additive processes further enables systems integration through a network of internal voids. These internal pathways can be designed to support infrastructure for rainwater harvesting and drainage, interior climate control, ventilation, and electrical and data transmission. Approaches that promote functional integration reduce the escalation of components used in construction. Over the last century, the trend has continuously moved toward an increase of infrastructural systems and assemblies that comprise the total structure (Kieran et al. 2004). This contributes to disproportionate increases in construction cost and systems coordination. Intelligent design based on additively manufactured systems could support the reversal of this trend or, at minimum, dampens its impact.

Interlocking and complex mated surfaces can be embedded within connecting elements, restricting improper assembly. Fastener-free, self-locking, and load-specific connection strategies can be designed for optimal assembly to potentially reduce construction schedules. A catalog of joinery types generally associated with wood and timber construction may prove applicable where previously infeasible due to traditional metal fabrication constraints. The connections developed for steel are inherent to the profiles and fabrication methods available; however, hybrid fabrication offers the potential to reconfigure the relationship between mating surfaces. This gives credence to alternative strategies modeled after the intricate interlocking found in Japanese joinery. The gooseneck tenon shown in Figure 8 would be infeasible within an assembly of stock steel profiles, but may serve as an appropriate model for connections between additively manufactured elements.

The "high-level functional integration" achieved through additive processes is noted by Achim Menges (2008) in his essay "Manufacturing Performance." In this examination, he presents the challenges of construction scaled implementation and the inverse relationship between scale and resolution associated with fabrication time. He effectively demonstrates the limitation of additive systems to provide material delivery rates that effectively operate in both high-resolution and bulk deposition. This challenge is particularly relevant for implementation of highly articulated components with functional integration. While this inverse relationship exists, metals are not challenged by this as significantly as the thicker load-bearing materials examined within his essay. The relative thinness and minimal mass required for metal structures alleviates some of this condition. A solution to this problem lies in the way material is delivered and fused within our proposed system. The laser used to fuse material is focused before passing through the coaxially delivered powder stream. Within most (if not all) additive manufacturing systems, the optics used for focusing is fixed and does not allow for in-line control during the fabrication process. A zoom homogenizer offers this type of control of the laser beam's size but is generally designed for applications such as heat treatment rather than cladding or deposition. Coordinated control of the beam diameter, laser power, and material delivery rates would enable nimble negotiation between states of high-resolution and high-speed bulk deposition. In addition, this feature provides more effective deposition for path planning based on dissimilar path width and can more efficiently deposit material within cross sections of non-uniform thickness.

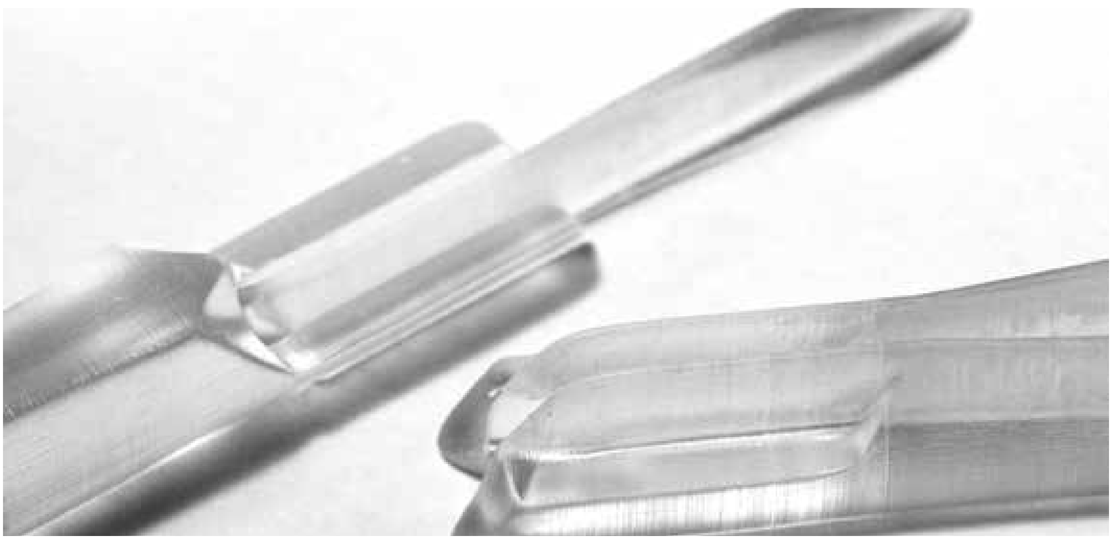


Figure 8: Connection strategy based on the gooseneck tenon observed in the joinery of Japanese woodwork. The prototype demonstrates effective self-locking and alignment of elements. An algorithmic design approach capitalizing on advanced manufacturing will enable solutions such as this.

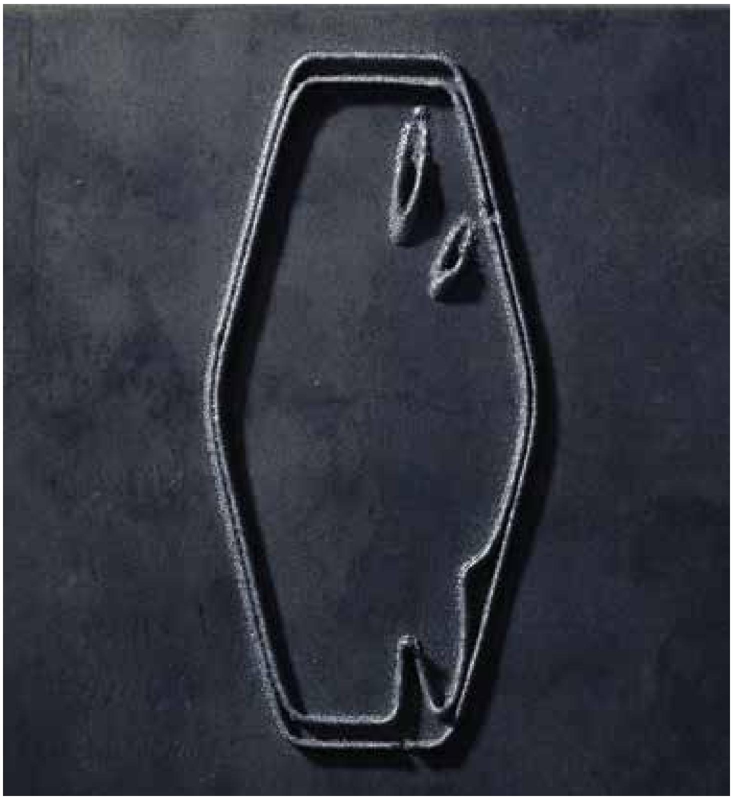


Figure 9: Experimental results from the initial contour-slicing algorithm demonstrated effects of signal timing delays and overbuild associated with inconsistency of velocity along path. Gaps produced by signal timing issues have been resolved, but further development is needed to regulate interdependent parameters based on real-time velocity feedback.

DIFFERENTIATED COMPOSITION

Building upon the resolution of design possible with additive processes, Neri Oxman (2010) proposes a more nuanced commitment to material through her theory of variable property design (VPD). VPD, as described by Oxman, places material first in a bottom-up approach. The relevance of this approach provides cues regarding the multi-scaled arrangements of spatial voids and heterogeneous material distribution. This approach applied to metals has compelling repercussions on the design of heterogeneous alloys and functionally graded structures. The metals used for direct metal deposition include (but are not limited to) aluminum, steel, and titanium. The micro-powders available provide a broad range of compositions designed to achieve localized mechanical properties. Through numerically controlled deposition rates, material properties can be modulated to address various design criteria and offer a high degree of structural performance. Base metals can also be combined with other alloying elements such as chromium, molybdenum, nickel, silicon, or tungsten carbide. These can be supplemented selectively to components comprised of several compatible alloys within a single direct-to-part fabrication process (Kovacevic et al, 2002).

Compositions can be designed to locally increase hardness, high creep/fatigue resistance, or fracture toughness to minimize damage or crack growth in regions subject to plastic deformation. Similarly, corrosive properties can be selectively determined to achieve functional criteria and/or aesthetic qualities. Insulated and conductive pathways may even prove feasible as embedded infrastructure. In addition to the mechanical properties noted, other physical properties can be modulated, including specularity, reflectivity, emissivity, and color. This can be achieved to promote sensual qualities or other aesthetically driven aspirations. Combined with surface treatment and other post processing applications, oxidization and bluing effects can have locally controlled responses. Each of these criteria has inevitable design implications for the element's cross section and surface appearance, potentially contributing to emerging affect at an organization level.

DESIGN THROUGH FABRICATION WORKFLOW

The integration of algorithmic design methods featuring optimization routines and FEM response mechanisms with file-to-fabrication processes presents notable challenges. For this reason, material- and fabrication-based research runs parallel to programming development of design-to-fabrication tools. These ad-hoc applications contribute to the testing and investigation process by augmenting the available toolset. As each component of research satisfies its objective, prototypical modules of code are integrated within a code library or framework written in C++. This design-to-fabrication framework serves as the backbone for a prototypical architectural scaled implementation of additively manufactured metal structures and extends from conceptualization of a global system incorporating structural feedback based on FEM analysis through discretization of node components, path planning, and signal control for robotic fabrication.

Preliminary path planning definitions developed in Grasshopper have been post-processed with the assistance of Kuka|prc, developed by Johannes Braumann. This application plug-in offers versatility and expedience for prototyping KRL programs and integrates seamlessly within a Rhino/Grasshopper platform. Workflow limitations related to computational efficiency are nevertheless apparent as part geometry's size and complexity increases. High-resolution paths are needed to fully describe the instruction sequences for fabrication of such parts. Similarly, the instructions generated test limitations for the robot controller (Gardiner et al. 2014). Unlike most operations for which industrial robots have been employed, additive manufacturing requires tighter path positioning tolerances and minimal variation in velocity during the deposition process (fig. 9). Vertical spacing of contours and tool orientation must be coordinated with deposition rates to ensure proper delusion for overhangs and unsupported inclines (fig. 10). Internal fill algorithms also require special attention in regard to

Figure 10: Studied for unsupported inclines and overhangs. Investigations have been based on three approaches: vertical axis of tool orientation, tool orientation based on slope, and coordinated orientation between tool and part manipulated tilt-rotary platform.

Figure 11: Hatching or fill algorithms for cross sectional path planning. The results show porosity encountered when paths are not properly spaced for delusion between adjacent passes. This is particularly evident in areas where paths diverge related to increased wall thickness. Further research is targeted for use of zoom optics to provide inline control and variation of path width.

spacing to eliminate porosity that adversely affects the mechanical properties (fig. 11). These factors contribute to lengthy instruction files that exceed sizes supported by Kuka's KR-C2. This limitation is partially alleviated by breaking instruction files into smaller chunks of code. To achieve this, a KRL parser was developed to divide instruction files according to specific tokens within the program. These subdivisions are then compiled into separate batches of instruction and formatted into subprograms, which can be called from a corresponding master program that is also automated during the read/write process.

Due to the apparent lag associated with performing these calculations for a single node, the potential to automate this process for large collections of nodes is improbable and certainly computationally inefficient within the current workflow. Added complexity and increases in KRL instruction needed to describe material composition on a point-by-point basis further compound the limitation of the current workflow. These limitations are not unique to this platform, and in general most CAD/CAM software fails to anticipate design processes implementing heterogeneous composition (Knoppers et al. 2010). While these limitations represent challenges, solutions are being researched. One example that may serve as a model for implementation is being developed by Andrew Payne and Panagiotis Michalatos (2013). Their proposed software introduces several compelling approaches that extend well beyond the scope of this paper, but a fundamental shift towards graphics processing and shader-based calculations offer clear computational advantages.

CONCLUSION

The proposed system for hybrid additive and subtractive manufacturing presented yields an expanded domain for design research. Structural performance and the design of lightweight structures are key areas for implementation of additively manufactured metals. The ability to integrate various functions and calibrateheterogeneously composed alloys locally demonstrates significant implications for the synthesis of aesthetics with performance-driven criteria. Technê as an intelligible participation between maker and matter contributing to poiesis is evident. Further investigation of this theoretical framework can only provide resolution to our understanding of the dependencies at play. Driving potential for emergence through material engagement must, however, be demonstrated empirically through a larger body of research based on this methodology, as well as through refinements to the proposed manufacturing systems. While current investigations show promise, many challenges must be addressed before the realization of intricate and high-resolution structural systems comprehensively exemplify many of the features discussed.

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plyAbility: New Parametric Models for Laminate Composite Material Manufacturing in Architecture

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INTRODUCTION

Advances in composite materials and corresponding manufacturing techniques, specifically computer numerical controlled (CNC) machining, necessitate new models for the instruction of digital fabrication in architectural education. With the ease of design and manufacturing platform development brought about by the emerging cultures of visual programming (e.g. Grasshopper and Dynamo) and more intuitive, dynamically typed scripting languages (e.g. Python and DesignScript), the applicability of precision toolpathing within a freeform parametric modeling environment needs to be reevaluated. The current climate of image-driven form-making has inadequately addressed the opportunities of downstream manufacturing, proving shortsighted in preparing students for the realities of a changing architectural profession increasingly allied with fabricators by means of shared models and data sets.

To this end, a graduate seminar on the topic of computer-aided construction has recently been developed that includes new computational models. In this seminar, Master of Architecture students at the Pratt Institute's Graduate Architecture and Urban Design (GAUD) program create speculative architectural assemblies from glue-laminated composite stock. The assemblies range in function from shading devices to structural bays, and in scope from individual masonry units to entire cladding modules. Once the base geometries and their parameters are formalized with a sufficient understanding of downstream fabrication constraints, material performance can be achieved solely through the manipulations of manufacturing-based analytical thresholds within the parametric definitions. This novel design-for-manufacturing process acknowledges both creative and analytic thinking at both ends of a complex workflow and is repeatedly tested in the context of ongoing CNC-machined prototypes.

CURRENT APPROACH

There is a tendency in academia toward repetitive, cellular patterning in CNC-fabricated work rising out of formal tendencies in parametric design, such as the ease with which isoparametric subsurface routines and related surface parameter space hosting methods can be achieved, and the logistical reali-

Figure 1: CNC router machining a mold for a bent wood chair back design driven by a single, unarticulated NURBS surface.

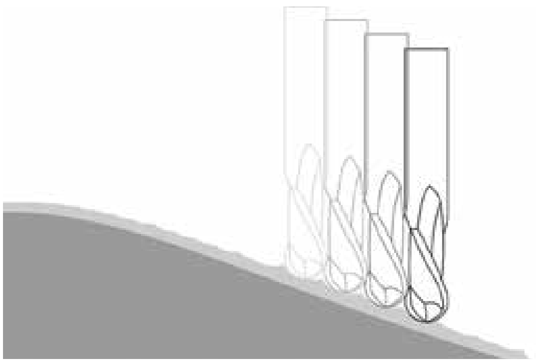


Figure 2: Diagram of end mill step over relative to stock artifact.

ties of construction, wherein design surfaces must be "broken down" or discretized into constructible units. What results from this may seem like simple patterning, but could perhaps be thought of as a hybrid of discretized (the repetitive patterning derived from parametric software) and monolithic (the volume of stock being machined) systems. The difficulty in describing these complex forms with toolpathing leads to manufacturing inefficiencies, particularly if the forms have not been designed with the means of manufacturing in mind.

Looking outside of architecture, academic programs in industrial design serve as good precedents for design-for-manufacturing curriculums, curriculums that emphasize the constraints and opportunities of downstream manufacturing as a primary design driver. However, the forms being machined in such programs are inherently different from those being pursued in architecture, tending toward monolithic forms, such as the body of a car (broken up into components like the hood and doors, but certainly not to the extent of a typical architectural panelization) or furniture. These unarticulated surfaces can be easily described by toolpathing, allowing manufacturing processes to be optimized (fig. 1). Furthermore, these objects are designed for mass

Figure 3: Isocurve-based stock artifact in Baltic birch plywood, revealing ply glue lines.

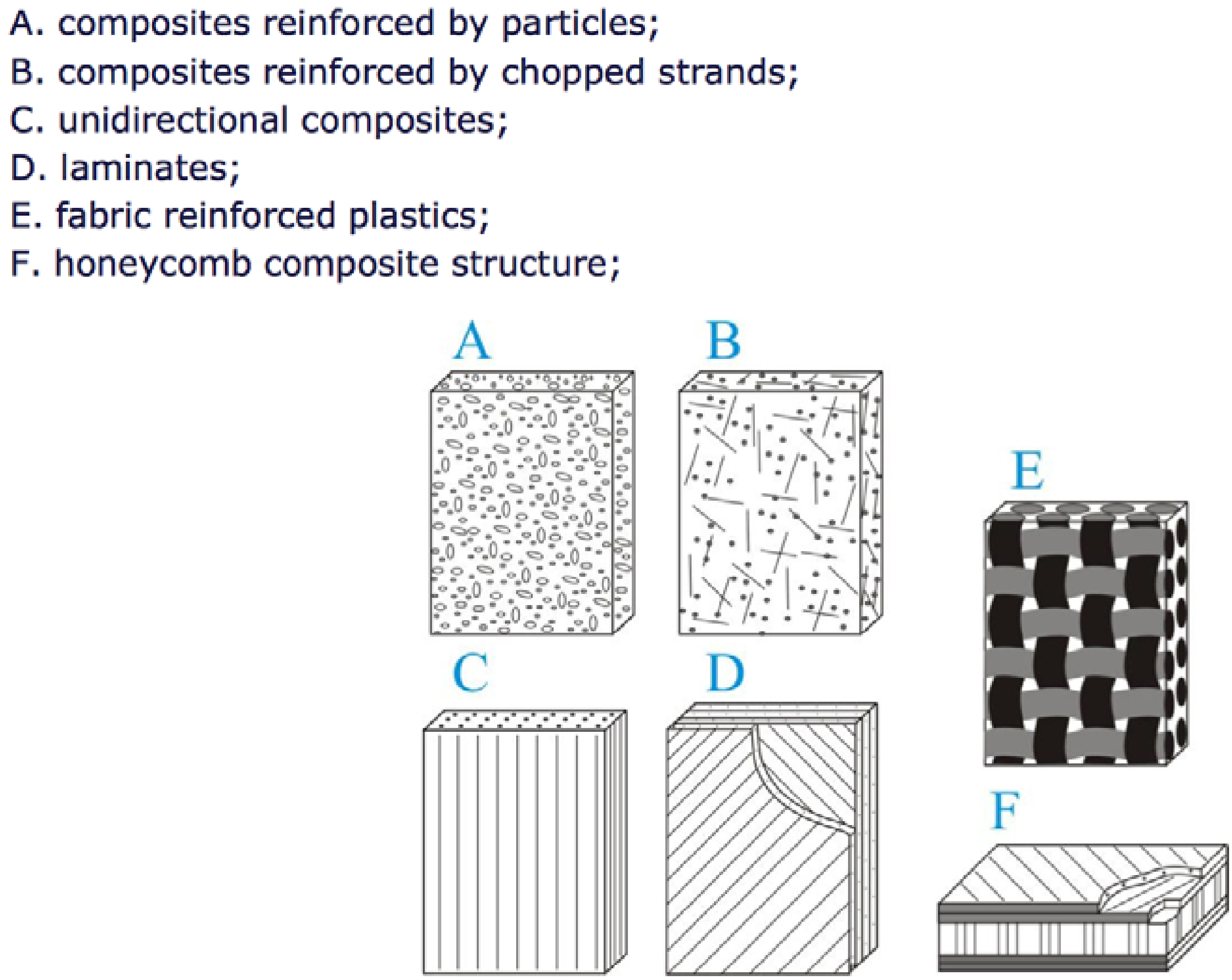


Figure 4: Common types of composites.

production (something that architecture generally is not), furthering efficiency and cost savings through repetitive production.

Therefore, it would seem that architecture is stuck between a particular aesthetic agenda and the unavoidable fact of its manufacturing inefficiency. This is where the classroom investigation typically ends—some small technological proficiency gained in the process, but lacking critical examination. For the "plyAbility" seminar, this is where the questions begin: How can we harness the unique capabilities of parametric software, not exclusively for formal generation, but also to define an explicit relationship between formal language and means of manufacture? How can such a workflow, in addition to potentially increasing manufacturing efficiency, push back on said formal approach; in other words, how might considering manufacturing limitations and opportunities impact aesthetic? And ultimately, how might we integrate architectural performance along the way?

Performance inherent to the material volume itself, when considered, has been something tacked on to the artifacts of the CNC machining process. While CNC artifacts, which are patterns of material volume intentionally left behind on a finished piece (fig. 2), could conceivably aid in phenomena like rainwater runoff directed by machined grooves, they're also liable to create additional problems. These include difficulty in cleaning and maintenance, animal perching and nesting, and thermal loss from increased surface area. Furthermore, the custom toolpathing that drives the CNC patterning motion, even if designed efficiently in the sense that it's inherent to the CAD model (such as extracted NURBS isocurves or subdivision surface face edge tessellations), is unlikely to be the most efficient and timely way to describe a surface for manufacture. In fact, it is only perceived as such due to its intentional coarseness, a timesaving strategy not intended to fully finish the part to a smooth condition. And there are other, more practical concerns: The pointing and cusping resulting from patterning is subject to

Figure 5: Suction cups of various sizes on an octopus's tentacle.

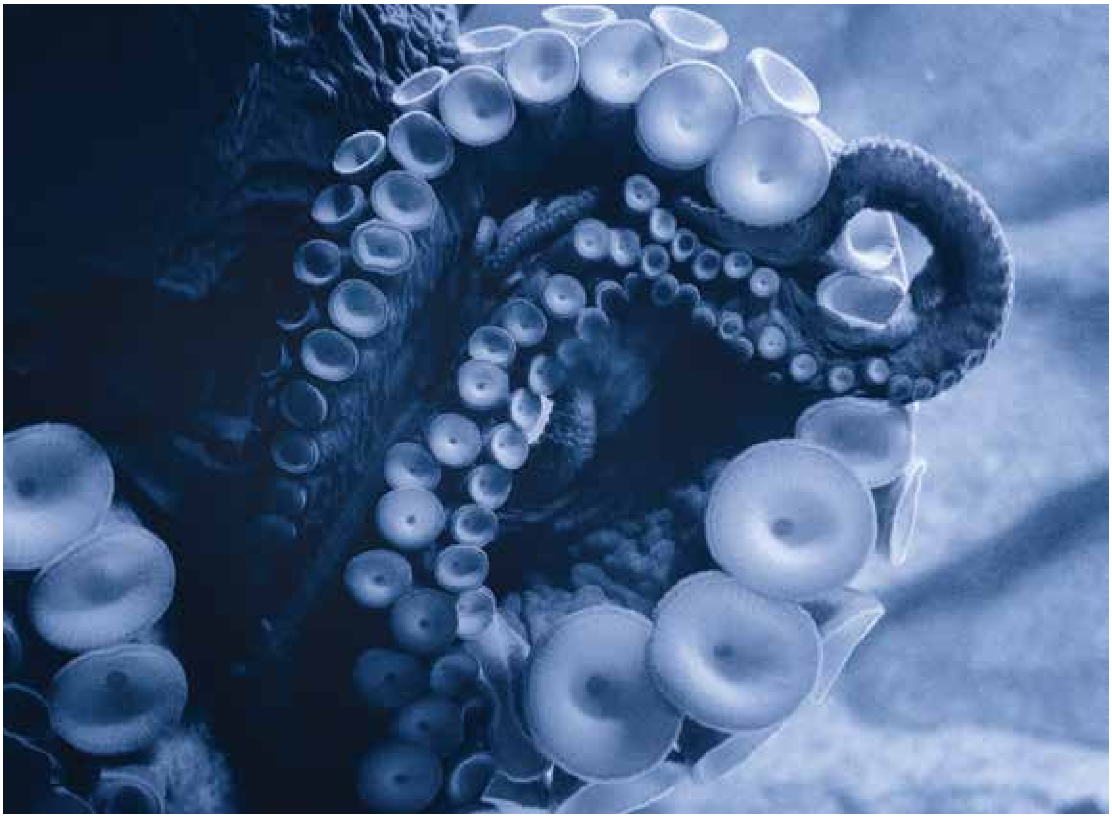


Figure 6: Gooseneck barnacles.

material damage, such as splintering and chipping; the finely articulated detail is nearly impossible to properly finish via sanding and coating (fig. 3); and the increased surface area makes secondary manufacturing processes, such as the release of casted forms from molds or vacuum-formed plastics from bucks, extremely difficult.

COMPOSITE MATERIALS

So what can be done differently? Composite materials may in fact be the additional factor necessary to extract performance from CNC-machined investigations. Composites are certainly not a new concept and can be found in contemporary manufacturing in products as diverse as fiber-reinforced sailcloth and the assembly of the iPhone, reliant more on adhesives and compression than traditional hardware.

Nor do composites have to be particularly complex (fig. 4). Though not typically discussed as such, plywood is a composite material, made up of thin layers of wood (birch, oak, maple, etc.) stacked with alternating grain direction and fused together with chemical adhesives and pressure. This yields performance (alternating grain direction creates two-way strength and reduces the chance of splintering and/or splitting the wood), aesthetics (the strata patterns of 3D forms machined in plywood are quite striking, particularly in contrast to the veneer), and practical economy (lower quality wood is layered in the interior with higher quality wood on the outside). In fact, the possibilities of composite materials are virtually limitless—any combination of two or more materials with matrix and reinforcement can be a composite.

For the purposes of the seminar, the composite material was to be a glue-lamination of any combination of:

1. Baltic birch plywood, for its aesthetic qualities as well as its relative rigidity.
2. Translucent white polycarbonate, for its light transmission quality as well as its ability to be bent with the assistance of a heating element.
3. High-durometer rubber, sufficiently rigid to CNC machine nicely, but pliable enough to allow for bending in the completed piece.

For even compression while the adhesives set, a vacuum bag is preferred to the inconsistent pressures offered by traditional board clamping. This change in approach is echoed in the words of Greg Lynn: "Assembly by chemical compounds doesn't involve the force of mechanical torque and pressure, instead it involves vacuums and cooking. There is a sea change going on in the world of construction and that is the shift from assemblage to fusion. In material terms this translates into a shift from mechanical to chemical attachments; more simply, things are built without bolts, screws, nails and pegs and are instead glued."[1] As Lynn mentions, no hardware is involved in making the laminated connections. This allows the entirety of the resultant composite stock to be CNC machined without concern that the cutters might collide with the fastening hardware, which can severely damage the tooling. The lack of an obvious connection detail also questions current paradigms in architectural tectonics. Turning again to Lynn: "Detail need not be the reduction or concentration of architectural design into a discrete moment. In an intricate network, there are not details per se. Detail is everywhere, ubiquitously distributed and continuously variegated in collaboration with formal and spatial effects."[2]

Figure 7: Parts of a feather.

Compositing techniques such as lamination, thermoforming, vacuum forming, vacuum bags, pressing, and casting open up the ability for a designer to machine a single volume composed as strata of different materials. Detail is encapsulated in various intensities across the material volume while, tectonically speaking, present nowhere. These manifold details are ornamental as well as performative across multiple metrics. Tom Wiscombe defines this as "meta-seaming,"[3] a shifting articulation of surface not constrained to any one particular system (isocurves, structure, venation, etc.) but fluid between many. For example, a crease enhances a material's ability to span but may also serve as a channel for drainage. These systematic relationships need not be so obvious—the relationship between tattoos and musculature is both subtle and grotesque (in its proper sense) but remains undeniably captivating.

With composites, the traditional restriction of working within the static properties of a solitary material has given way to new investigations into the dynamic material properties of composite material volumes. At any given moment along matter being machined, there exists a sophisticated ecology of materials and methods. Fac-

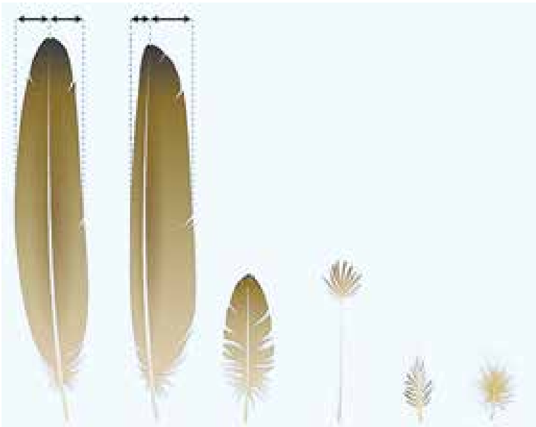


Figure 8: Types of feathers.

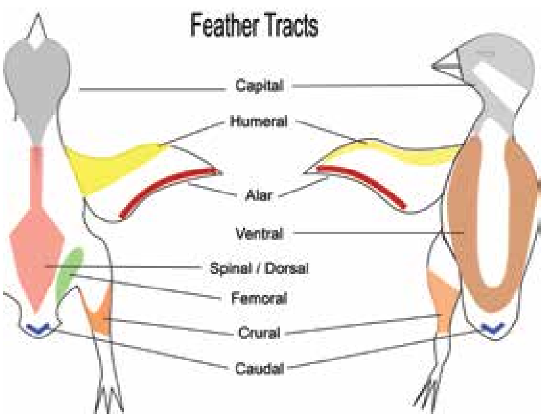


Figure 9: Feather tracts (pterylae) of a bird.

tors include cutting motion, cutter profile geometry, cutting depth, relative position of cutter tip to toolpath curve, material properties, material performance, and material aesthetic. Because the students' assemblies are machined from a laminate stock composed of a varying-property material stratum, they are capable of performing in both different manners (rigid flat vs. rigid fold vs. flexible bend/twist) and varying intensities (less to more folded, less to more flexible) at any given moment throughout the laminate, relative to the depth by which the stock is machined by CNC tooling. Parametric software like Grasshopper is the key to systematically controlling this depth and, by extension, the material's performance.

PARAMETRIC SYSTEM

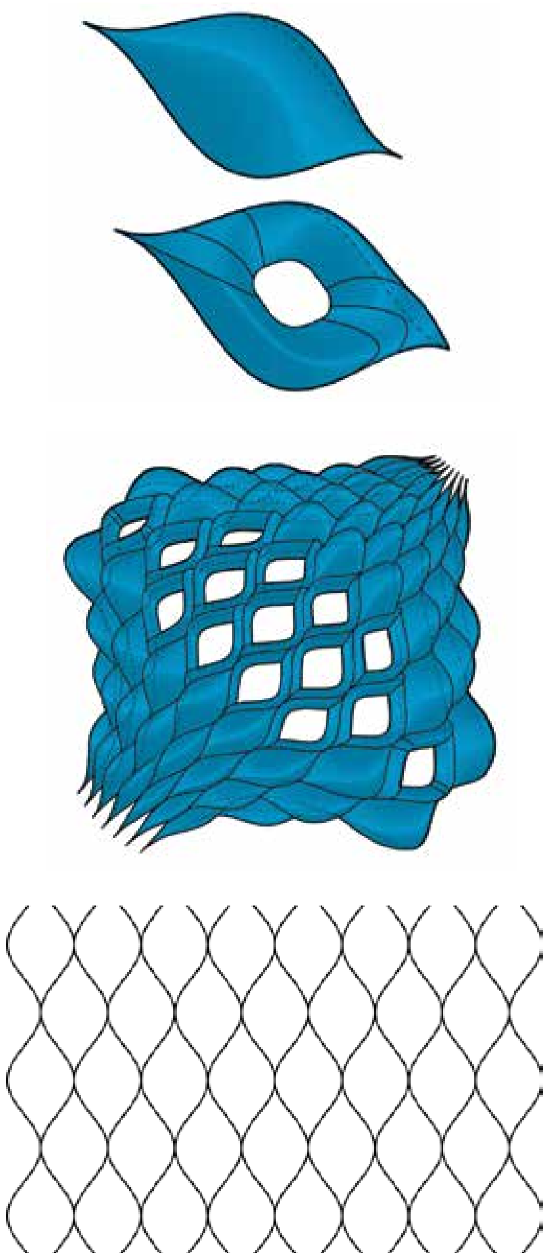
In order to extract the maximum range of performance out of a single volume of composite stock, a design system needs to be established that privileges neither discrete components nor exclusive functions. This is where the formal and performative ambiguity of our discretized-monolithic hybrid systems may be of use. Stephen Kieran and James Timberlake recognize this when they write: "The product engineer needs to take the blinders off and focus on permutations of elements rather than on single parts and separate materials. A vital new responsibility of the product engineer is the development of integrated component assemblies—modules, chunks, grand blocks—that cut across all the separate categories of material and function."[4] While it is difficult to identify a constructed precedent that strictly adheres to what Kieran and Timberlake are suggesting, it's quite easy to look to nature, and more specifically to animal integumentary systems, to begin to address such "permutations" of material and function. In this vein, students begin by identifying biomorphic precedents for the unit-based fields of their parametric models. Examples of this include animal integumentary and follicular systems such as bird feathers or pangolin scales (fig. 5), as well as fields of organisms such as barnacles clustered on a rocky shore (fig. 6).

Thought is given to these systems in four parts, where the first is to consider how the physiological forms of these systems could perform in both a traditional architectural sense (gills as ventilation, scales as rain screen, etc.) and a speculative sense based in architectural performance (the ability for a building to "grow" something akin to layers of feathers for insulation and a moisture barrier, respectively). The varying intensities or gradation of performance across such natural systems lends itself to a certain ambiguity best captured by Tom Wiscombe when he suggests: "A much more interesting and contemporary idea is to embed technology so deeply into architectural surfaces that it cannot be unwound ... where it is not clear what features are doing the work and which are excess ... Such formations, as in all of nature, are never the best of all possible solutions but rather good enough."5 Nature helps us to remember that we should not fool ourselves into pursuing fully optimized solutions (if there even were such a thing), but rather pursue flexible systems that can be functional and efficient but not overwrought, excessive and exuberant but not wasteful, and beautiful as a performative solution rather than merely a satisfying image.

The second part is to examine how the individual units in the system (a single feather or follicle) respond to performance demands in both the aforementioned gradation of intensity as well as in threshold transformations. For example, a contour feather might undergo a gradated intensity change in length and width based on aerodynamic demands along the edge of a bird's wing. The basic topography of the feather, the vanes and the shaft (fig. 7), remain topologically the same, but their characteristics or parameters adjust along the bird's body based on performance demands, changing all the way from long, stiff flight feathers to short and fluffy insulating down feathers (fig. 8). This is in contrast to a threshold transformation, which represents a fundamental topological change, such as the transformation from

Figure 10: Scaled pangolin coiled for protection.

Figure 11: Parametric unit types, grid, and units structured within grid and hosted onto body with threshold-based transformation from one unit type to the other.



feathered to non-feathered integument like the beak or the feet, where blood circulation can approach the surface of the body for thermoregulation.[6]

The third part is to consider how unit distribution and density create a field. Again looking to the bird, feather follicles are clustered within tracts known as pterylae (fig. 9), whereas featherless areas between tracts, where the follicles become much less dense for purposes of grooming, thermoregulation, and ease of motion, are known as apteria.[7] "Apteria" in the seminar's architectural assemblies allow for ease of motion, and they can also help to reduce the complexity and machine time of assemblies through a strategic reduction in pattern articulation.

The fourth and final consideration is the shape of the host body in relation to the prior three considerations. Special attention must be given to how the system is impacted by the movement of the animal body host. While the end fabricated product is not necessarily kinetic, methods of animal motion relative to their integumentary systems may clue the students in to how the machined composite material could flex, bend, and twist most effectively. Examples of this include the coiled body of the pangolin relative to its scale overlay (fig. 10), and the inflation of a blowfish relative to its spike orientation.

Once students have a formal objective based on the above conditions, at least two unit types are parametrically modeled before being instantiated into a body-hosted grid, allowing for the generation of a field across which systematic gradation (within unit types) and threshold transformations (from one unit type to the other) may occur. Once the units are in place, the students analyze them for particular properties (surface area, volume, height, curvature, etc.) in order to get a sense of existing data ranges in the definition so they may set their thresholds accordingly.

The initial analysis is just a starting point, as these thresholds will eventually relate more directly to the CNC machining process. For example, if a CNC cutter is unable to fit within pockets under a certain diameter, units with apertures would automatically be transformed into more easily machined solid units (fig. 11). This avoids time-wasting formal idiosyncrasies, such as the tool only being able to partially machine out a pocket, leaving haphazard divots in the work piece. Using these thresholds, the designer now has an understanding of downstream manufacturing limitations and can control transformations relative to tool fit or reach, or even whether or not material will delaminate, warp, chip, splinter, burn, scuff, or otherwise fail given its geometric properties (tall, thin) relative to its material properties (directionality of lumber grain or thermoplastic extrusion). Design considerations, performance benchmarks, and manufacturing concerns are thus linked in both computational (design method) and tectonic (built product) fashion (fig. 12).

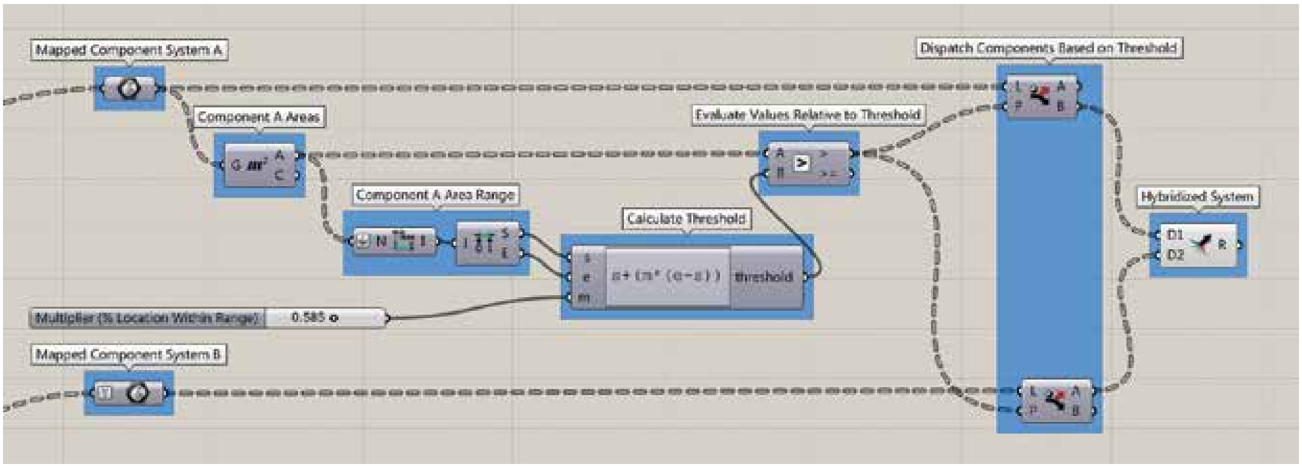


Figure 12: Grasshopper snippet describing the threshold-based transformation from one unit (or "component") system to another.

MACHINING PROCESS

There is a tendency among students to prototype the entire design straightaway; their desire for the completed image of the piece must be overcome so that they first concentrate on solving issues of material performance. Their objective should be to extract the maximum amount of knowledge possible each time they go to the CNC machine, establishing proof of concept prior to pursuing a complete machining of their design concept. If only a small portion of the prototype is expected to bend and the rest is rigid, the students are encouraged to limit their initial prototyping to that portion which is bent so that the bending performance of the material can be proven prior to spending a large amount of time prototyping the entire design, only for it to fail in key areas (fig. 13). This strategic approach, in which we are not simply pumping out physical recreations of a digital model but also learning how to investigate actual material performance, seems obvious, but it is perhaps the single most important aspect of the course—and one of the most difficult student habits to overcome.

When it comes time to glue up the materials, work must be done quickly so that the adhesives do not set prior to the material being placed in the vacuum bag. Wood-to-wood mating is easily done with wood glue, typically Titebond I, or Titebond II if increased set time is required for larger surface areas. The rubber and the polycarbonate, however, lack surface friction and are difficult to get to adhere. Therefore, it's recommended that the mating sides of both of these materials are scored with a knife in a diamond pattern and, in the case of the polycarbonate, additionally sanded with a high-grit sandpaper to increase surface area for adhesive grip. For wood-to-plastic adhesion, any two-part epoxy, such as Gorilla Glue, works quite well. However, cured epoxy is brittle and rigid, which does not work particularly well for the rubber, which is a much more malleable material than the others and requires a more flexible adhesive. Polyurethane construction adhesives, such as Liquid Nails, were tested to this end, but the glue line did not compress to the desired consistent hairline depth. Ultimately it was a general-use adhesive by Liquid Nails that proved to perform the best, both in the glue-up process and later when under the duress of CNC machining—the aptly named "Perfect Glue."

After the materials are laid up, the composite stock is wrapped in butcher paper (to prevent it from adhering itself to the inside of the vacuum bag) and placed within the bag on a grooved palette (fig. 14). This palette encourages air flow underneath the stock, while a plastic mesh drape assists air flow over top of the stock. The part is stabilized within the bag by creasing the bag at the corners of the stock with palms placed firmly against each side of the stock corners. This keeps the material layers from shifting while the glue is wet and has the added advantage of preventing the bag from dimpling over the top of the stock corners (it's also recommended to rasp the corners prior to glue-up). While this process can be quite precise when performed properly, it's recommended to leave a quarter to a half-inch tolerance between the dimensional extents of the part being machined and the dimensions of the stock.

In addition to the physical prototype, the deliverables for the course include diagrams illustrating the single parametric unit and its critical parameters, heat maps indicating the intensities of various parameter gradations across the field, Boolean diagrams of threshold changes, renderings or drawings of the field instantiated onto a host body or surface, and anything else required to explain the process. Perhaps the most critical drawing is when the students export the resultant stock from the CAM package, which is a different geometry than the initial surface input, and contour it relative to the locations of their glue lines (fig. 15). This verifies that the cutter is machining to the depth of stock required to release particular material strata in order to achieve the desired performance.

Figure 13: Prototype testing for possible bend angles.

SEMINAR CASE STUDIES

Students Ulrika Lindell and Erik Davin Nevala-Lee began their project by studying the intricate Radiolarian mineral skeleton (fig. 16), known for its efficient lightweight structure. An alternating cellular grid was instantiated across multiple surface strips (fig. 17), with individual units becoming more or less squeezed across the length of the strips by multiplying the deconstructed V domains of the isoparametric subsurfaces by the values of a willfully manipulated Bezier graph (fig. 18).

From this study they devised a concept for an architectural assembly in which cross-bracing elements could be constructed from two bendable strips of composite stock. Toward their extremities, the strips would be thick and rigid and the light apertures would be at their largest (fig. 19). Toward their midsections, the strips would taper to a thin layer of rubber and the apertures would flip from void to solid, providing a series of rigid islands to help structure the bend (fig. 20). A machined slit in the piece would allow for a portion of it to peel off and form the basis of a connection with a second strip, thus forming the cross-bracing member.

The strips needed to be machined on both sides, either via a flip-mill or by machining the two sides separately and joining them after the machining process. This meant that in order to machine a single cross-bracing element, there were a total of four CNC setups, consuming a massive amount of machine time despite the use of efficient toolpathing strategies. Machine time was the largest limitation of the projects from the first semester of the course, so in the second course, the concept of apteria would be reintroduced as a means of strategically reducing articulation in order to reduce machine time, with the goal that more substantial prototypes could be produced. Any articulation that appeared to be purely ornamental with no conceivable function would be eschewed for more straightforward manufacturing.

One project that was particularly successful in this respect was a cell phone privacy booth design by the student team of Linnéa Moore, Andrew Sutton, and Olivia Vien. The students were interested in how the instantiated units might splay as the rubber bent, much in the way scales might adjust as the pangolin rolls into a protective ball, or the manner in which the blowfish's spikes move from parallel to perpendicular to the fish's body upon inflation (fig. 21). In order to achieve splaying and assist with overall bending, a small cutter was used to trace the leading edges of the units to partially release them from the stock. This method of tracing islands of solid material laminated to the rubber, when used for scoring (partial depth piercing) rather than cutting, was also useful in reducing the tendency to delaminate via the shear forces occurring at the glue line between the rubber and the wood or plastic islands (fig. 22).

Figure 14: Students working to stabilize material within a vacuum bag.

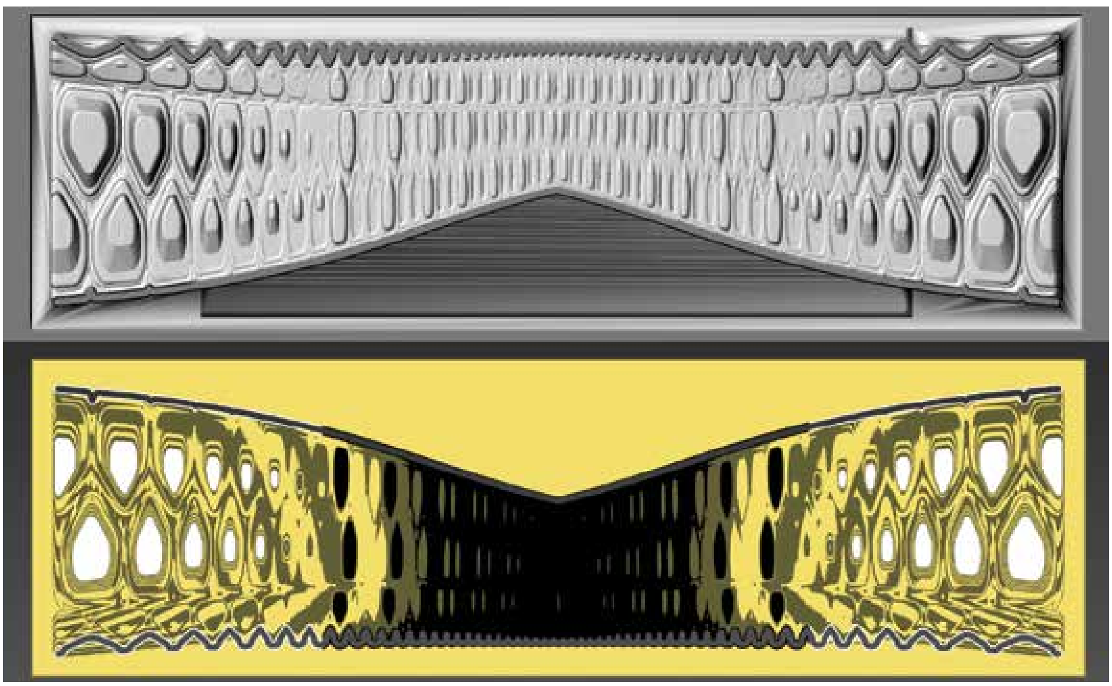


Figure 15: Contour drawing indicating glue line and material strata locations in exported RhinoCAM stock result.

Figure 16: Radiolarian mineral skeleton.

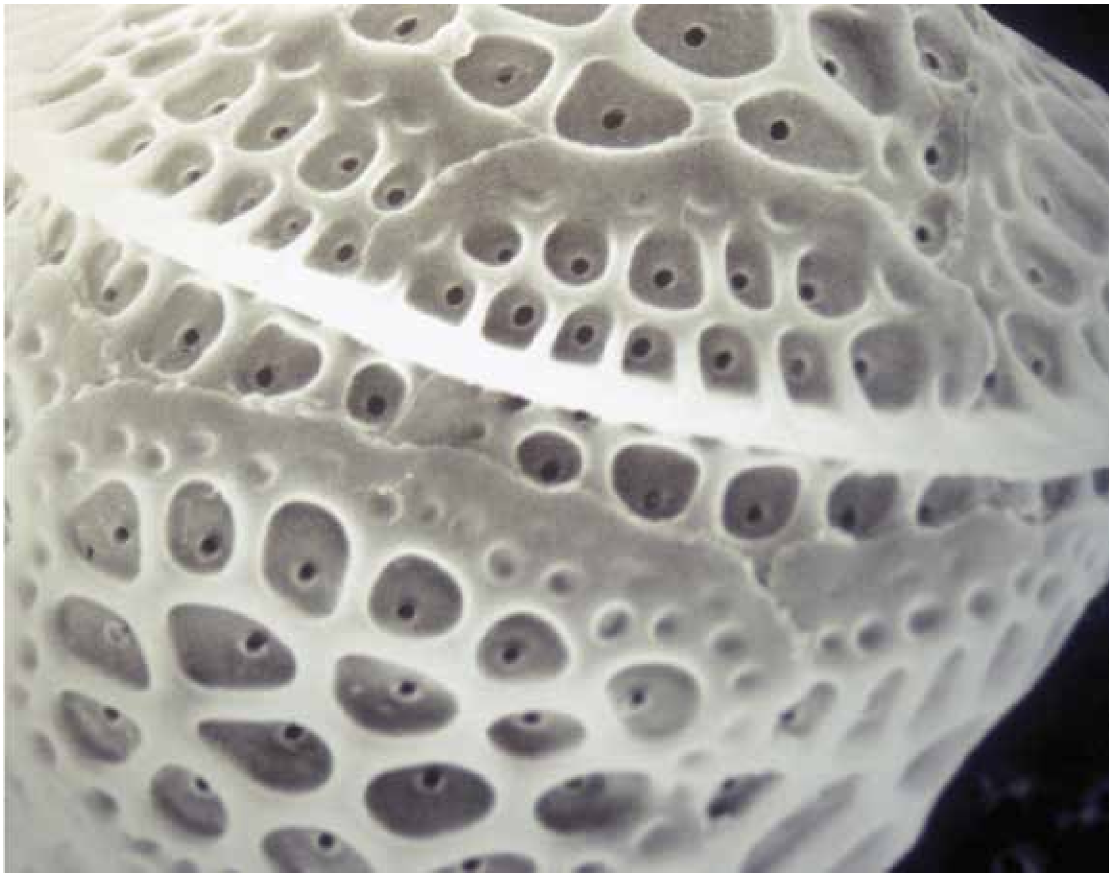
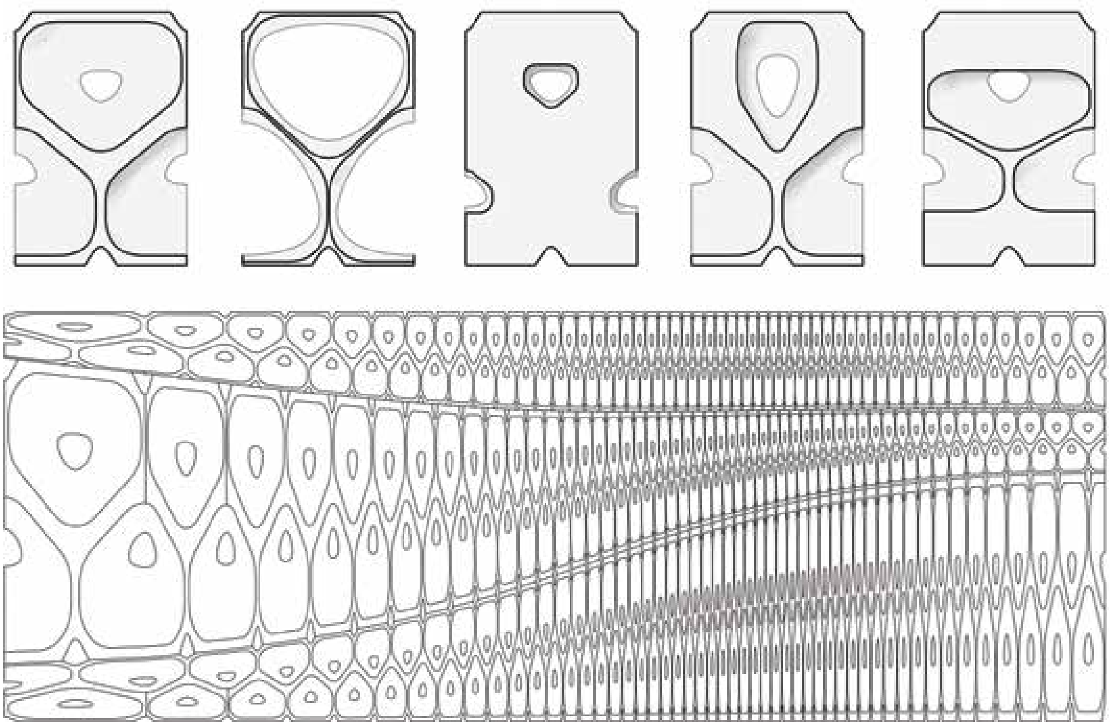


Figure 17: Initial parametric study.



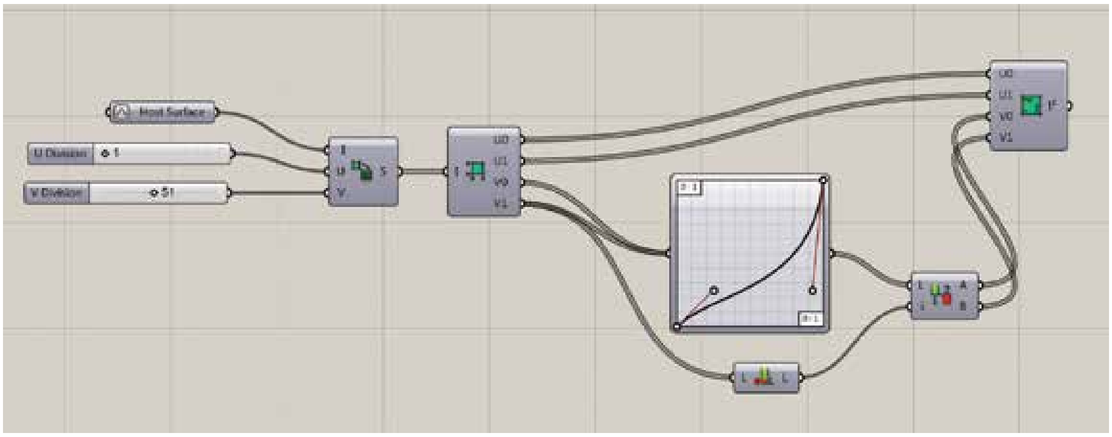


Figure 18: Grasshopper snippet showing Bezier-based isoparametric subsurface V domain gradation.

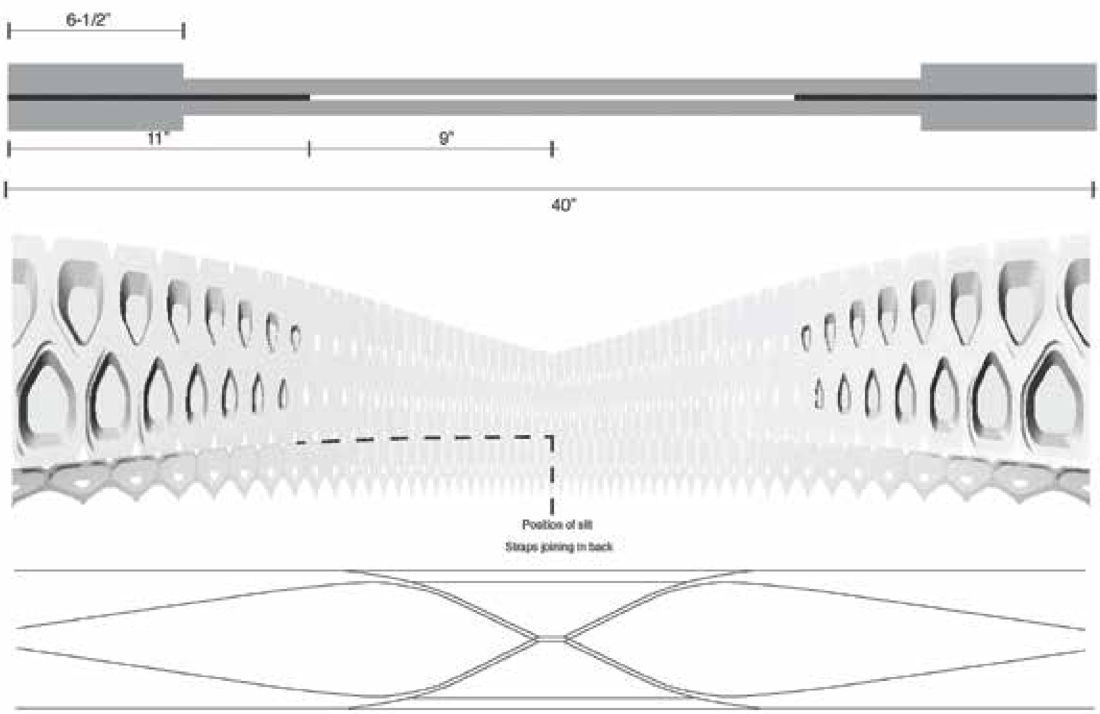


Figure 19: Composite material lay-up, machined stock result, and elevation of cross-bracing assembly.

Figure 20: Machined composite stock strip.

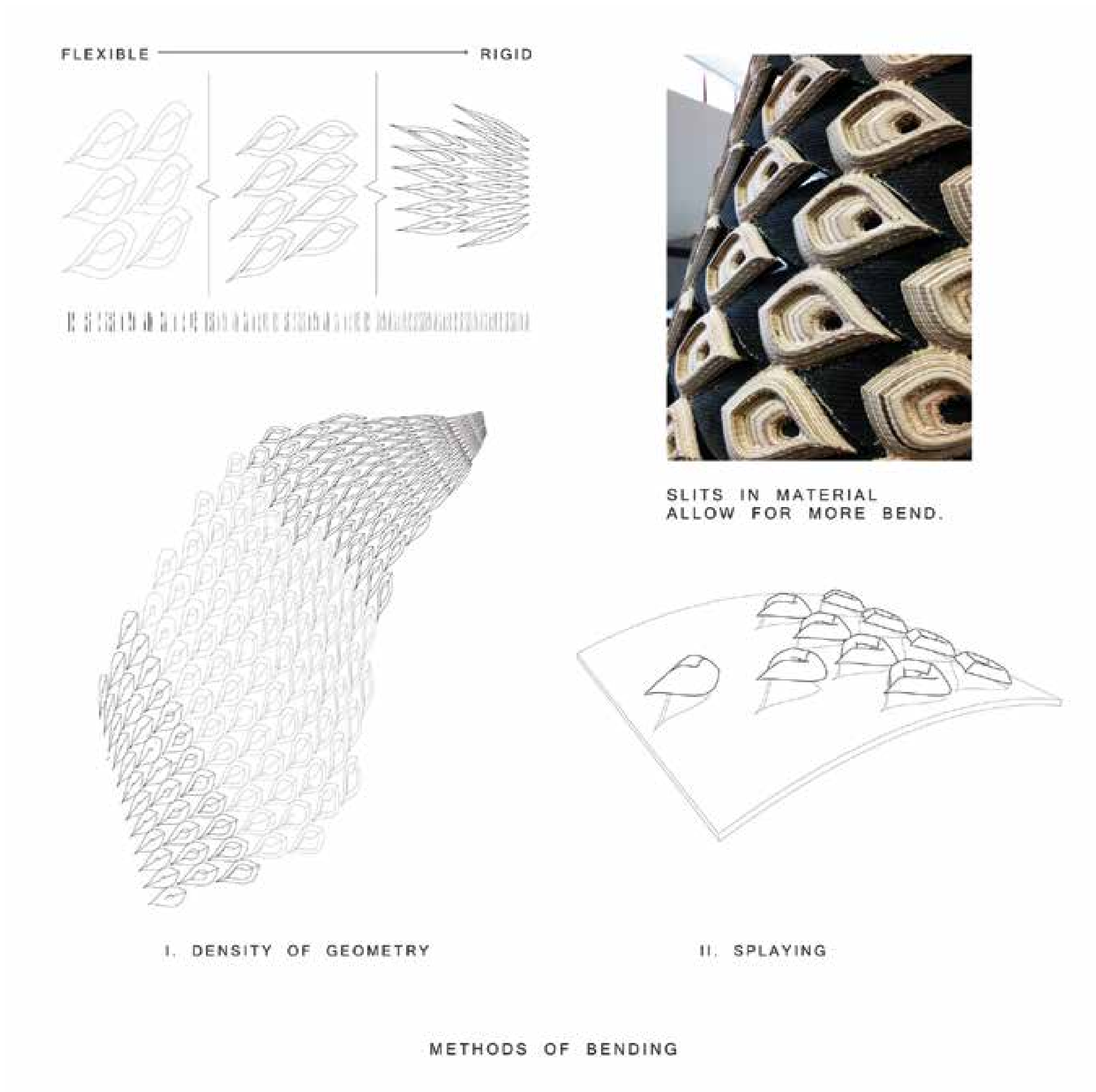


Figure 21: Unit density and splaying strategy.

Instead of articulating the entire booth, the students limited articulation to those areas that required cutting to release bending and/or light-filtering performance, and then faded into unarticulated, broad surfaces which served more of a structural or space-defining function. In this manner, they were able to produce a more substantial assembly than had previously been possible (fig. 23).

SUCCESSES AND LIMITATIONS

Successful projects were judged by a high output to machine time ratio, indicative of both efficient toolpathing practices and strategic distribution of articulation across the stock. Further efficiencies were gained when analytic thresholds were dialed in correctly such that no geometries existed which could not be fully reached and machined by tooling.

Material performance was another factor of success. Completed assemblies that were able to flex, bend, and twist along areas strategically milled to the depth of the rubber, and/or transmit light or be rigidly folded via a heating element along areas strategically milled to the depth of the polycarbonate are good examples of this. There has to be some restraint here—if too much of the rubber is released, the assemblies lack structural integrity.

Many of the limitations along the way relate to the materials themselves. As mentioned previously, the smooth surfaces of the plastic and rubber make them difficult to bond with other materials. This also hampers the stock's ability to be vacuum-held on the CNC router's spoil board, and in many cases, students had to resort to mechanically fastening their stock to the router bed. This reduces the range of material that can be machined safe from fastener collision. To an extent, vacuum holding could be assisted with double-stick tape and larger stock footprints, but any stock motion during a machining process is troubling indeed.

The flexibility of the rubber is also a challenge. Materials need to stay rigid while they are being cut, but rubber tends to flex under the cutter. If the cutter is rubbing against material rather than removing it, the increased friction leads to tool overheating, which in turn hampers its ability to cut cleanly, so the whole thing becomes an unfortunate feedback loop (not to mention the acrid smell). This can be overcome by switching to a specialized down cutter when machining the rubber, and limiting any toolpathing of the rubber to simple two-dimensional cuts rather than fully three-dimensional surface machining; however, specialized tools mean increased budget and setup time, so compromises are often made. The flexibility of the rubber also means that composites which have an interior rubber ply exposed by machining both sides of the composite stock cannot be flip-milled (machined in two positions), as the stock sags in those areas where it is not supported by other material plies. Therefore, assemblies with rubber cores are typically milled in two parts and joined after the machining so that the rubber strata can rest on the spoil board while machining.

Overall, it is difficult to obtain the kind of unfettered access to the lab that allows for sufficient fabrication iteration, meaning that students often have to take risks or test multiple aspects of their materials at once. However, as machine time is very expensive in the industry, this limitation likely mimics "real world" manufacturing constraints, and the ruthless time management efficiency it prompts in the students has educational value.

Future work in this area will look to materials and assemblies more suited to exterior construction and weather permeability, and will attempt to validate performance metrics with physical testing. Validation data would be integrated back into the computational model, effectively "teaching" it to simulate performance more accurately. Furthermore, this course would benefit from being removed from the seminar environment, which can focus too much on technological skills as a means to an end in themselves. Instead, the content could be situated within the context of the studio environment, where it could be critically applied to, and more directly driven by, issues of the constructed environment.

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Figure 22: Glue lamination and CNC machining process.

Figure 23: CNC machined stock and resulting assembly of cell phone booth.

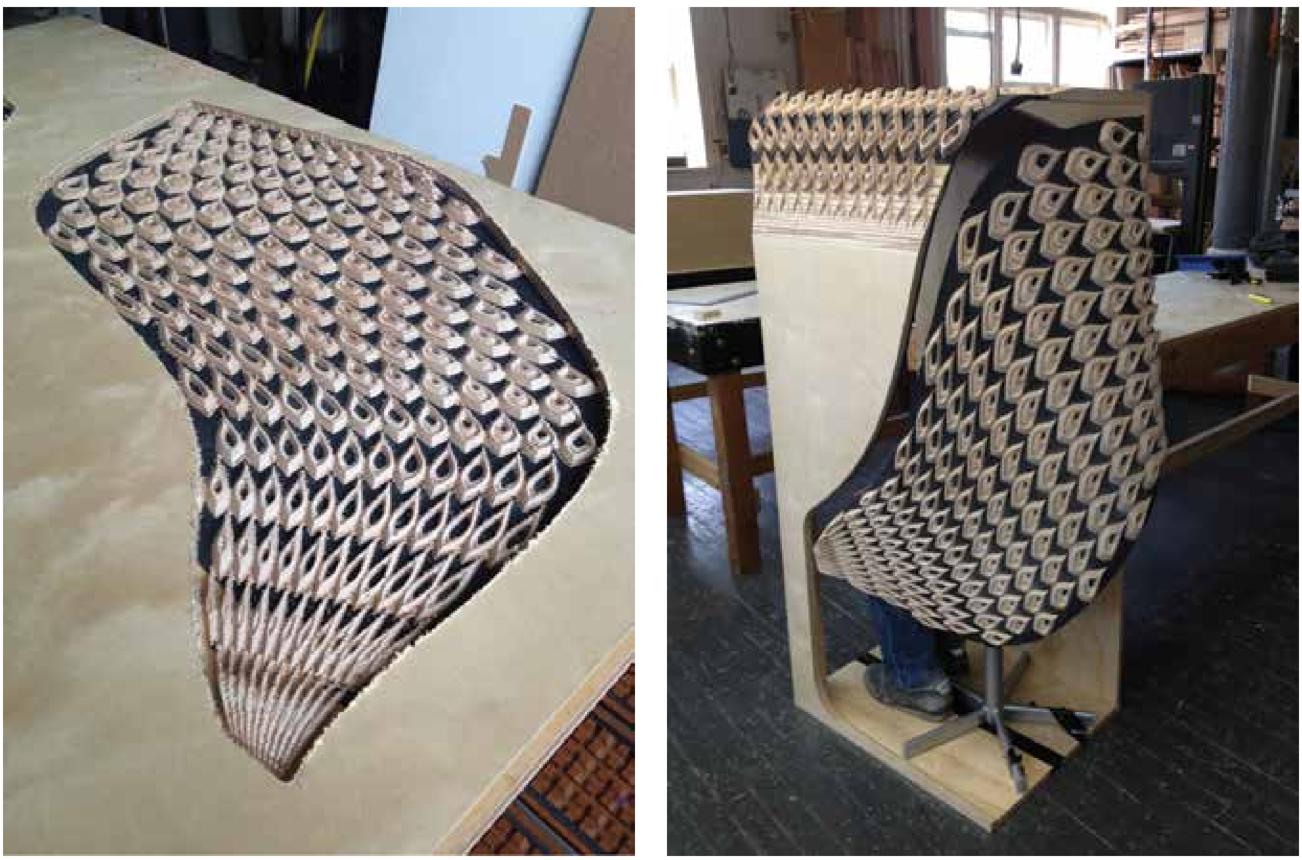

IMAGE CREDITS

Images by author unless otherwise specified below.

Title Image: Faroughi, Shahab and Sun Kim. plyAbility student work. Photograph. 2014.

Figure 3: Jordan, Trevor, Austin Weller, YoonJin Kim, and Brian Turcza. plyAbility student work. Photograph. 2012.

Figure 4: Kokcharov, Igor. "Classification of composites from book Structural Integrity Analysis." Diagram. 2010. Via Wikimedia Commons: Kokcharov, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Composites_Materials.png

Figure 5: Kilby, Eric. "Blue Tentacles." Photograph. 2015. Via Flickr: ekilby, CC BY-SA 2.0, https://www.flickr.com/photos/8749778@N06/17569669855

Figure 6: Pearsall, Peter/U.S. Fish and Wildlife Service. "Gooseneck barnacles (Pollicipes polymerus)." Photograph. 2015. Via Flickr: usfwspacific, CC BY 2.0, https://commons.wikimedia.org/wiki/File:Pollicipes_polymerus_(23812068786).jpg

Figure 7: "Parts of a feather." Diagram. 2006. Via Wikimedia Commons: Icea, Copyrighted free use, https://commons.wikimedia.org/wiki/File:Parts_of_feather_modified.jpg

Figure 8: "Types of feathers." Diagram. 2012. Via Wikimedia Commons: Anazxibia, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Types_of_feathers.jpg

Figure 9: Shyamal, L. "Pterylosis or feather tracts of a bird." Diagram. 2007. Via Wikimedia Commons: Shyamal, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Pterylae.svg

Figure 10: Wildlife Alliance. "Curled Pangolin." Photograph. 2010. Via Flickr: wildlifealliance, CC BY-SA 2.0, https://www.flickr.com/photos/wildlifealliance/9449651301

Figure 13: Sutton, Andrew. plyAbility student work. Photographs. 2014.

Figures 15-20: Lindell, Ulrika and Erik Davin Nevala-Lee. plyAbility student work. Photographs and Drawings. 2014.

Figures 21-23: Moore, Linnéa, Andrew Sutton, and Olivia Vien. plyAbility student work. Photographs and Drawings. 2014.

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Exercises in Plasticity: Retooling the Mold

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With the widespread availability of numerically controlled manufacture, design at all scales increasingly relies on countless, mass customized parts. These parts often respond to digital parameters more readily than to material parameters. Design is therefore increasingly responsive to technology rather than tradition. The following design research project attempts to combine tradition and technology in order to study the problem of seriality. The project combines craft traditions with digital techniques to explore a plasticity of parts and their impact on the conventions of material assembly or the making of larger wholes.

Despite the promise of rapid prototyping technologies, casting continues to produce three-dimensional copies more quickly, economically, and durably than rapid prototyping.[1] Beyond the known advantages of serial production, such as the interchangeability of standardized parts and the durability of continuous surfaces, casting, and its required tooling have received little academic attention despite their central roles in the production of seriality. Tooling refers to the mold used to produce copies of components or objects. When reconsidered in light of computation, the mold offers opportunities to rethink seriality through the introduction of plasticity.

The digital turn at the close of the twentieth century introduced two different models of part to whole. The first with its exploration of parametric design and scripting attempts to maintain visual coherence by preserving the dominant features of a part while changing its scale or orientation. This produces continuity with difference,

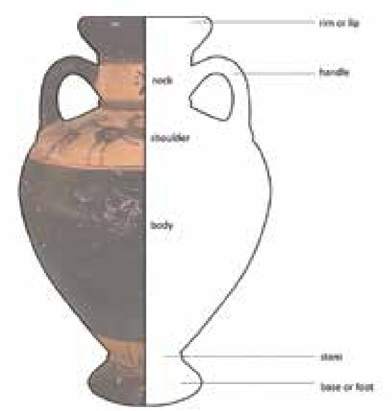

Figure 1: Greek Vessel Features

where continuity is primarily visual and difference characterizes the production, detailing, and resources associated with physical manufacture. The second attempts to recuperate some of the optimization lost in the former by mixing identically repeated parts with a smaller percentage of bespoke parts. This reintroduces uniformity of parts in order to manage the economic and technical constraints of difference. The following research project proposes a third model that combines the material and the numeric, allowing parts to vary in kind rather than degree without disregarding the impact on resources of unrestrained difference. This variation is managed logistically and technically in order to generate both a conceptual and procedural approach to seriality. The technical constraints of manufacturing are studied prior to the conceptual development of the project, allowing innovation of means to directly shape design ambition. The work proposes that non-unifrom seriality can spawn families of objects, allowing the study of variation to initiate new object lineages.

In the design seminar course after which this paper is named, graduate students in architecture and media arts at UCLA studied the relationship of cast vessel forms to their mold making logics. The course, co-taught with Noa P. Kaplan, asked students to reconsider the relationship of part to whole in the design of a vessel as both object and series. Central to this work was our shared interest in the formal, material, and technical parameters that configure vessels. Specifically, we were interested in understanding the influence of mold making on Western vessel forms.

Figure 2: Vessel Prototypes, 2:4:12

Figure 3: Vessel Prototypes, 2:4:12

We wondered if we might examine the problem of the mold as a way of bringing together tradition and technology. Here, the vessel is neither a high-volume, identically reproduced object nor a singular, handcrafted artifact. Instead, we approached the vessel with plasticity in mind. Plasticity refers to the capacity of a form to reflect the myriad of conditions under which it takes shape. These conditions may be material or abstract and are informed by historical and contemporary technologies. We wondered if plasticity might reinvigorate the status of the object as object series. By comparing one object to another in the same family, one discovers the ambitions of a given design proposal.

We studied casting processes and tooling constraints that influence the configurations of mass-produced vessels. *Tooling* refers to the manufacturing elements necessary for production. With casting processes, this includes one, two, or multiple part molds. A *mold* is defined as a fixed or restrictive pattern or form, but historically, the mold has been strongly associated with the first descriptor: the rigid, unchanging container. We asked students to consider the role of responsiveness in the design of tooling in order to exploit the potential of the restrictive, yet variable dimension of the mold. In *casting*, a liquid suspension is poured into a tool or mold and undergoes a chemical reaction. Typically, the mold determines the form of the resulting solid. The design of the mold reflects numerous production constraints, including part removal, mold fabrication, and mold durability and lifespan.[2] Students were encouraged to explore the opportunity for the liquid suspension and the mold container to inform one another, a collaboration of skin and substance. Students developed the design of the tool alongside proposals for a series of vessels. Static molds were reconceived as *responsive molds* capable of adaptation and variation due to the use of a flexible or reconfigurable mold material or through the rearrangement of components into multiple forms. The resulting cast objects explore plasticity, creatively circumnavigating the rigidity and identical repetition of the mold.

Students studied the historical development of hand-built, thrown, and slip-cast ceramic forms to understand their formal components and the impact of material behavior and production techniques on vessel silhouette, features, and serial production. The typical components of early Greek vessel forms—the rim, neck, shoulder,

Figure 4: Vessel 1 of 5, Dark Opulence

Figure 5: Vessel 3 of 5, Dark Opulence

Figure 6: Developed Mold (L) and Rotational Casting Machine (R), Dark Opulence

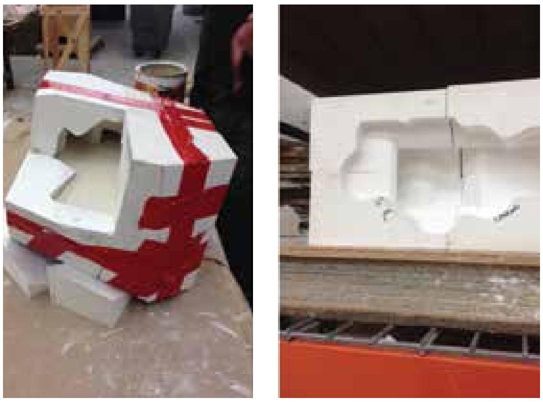

Figure 7: Eight-Part Tumbling Mold, Tumble

body, stem, and base—were studied to understand their morphological evolution in relation to function, ceremony, and classical aesthetics (fig. 1). A survey of contemporary vessels considered the relationship of morphology to material, craft, and industrial processes, and importantly, the technological mediation of material with mechanical and digital means.

Two lines of material exploration, slip cast ceramic materials and urethane resins, were explored to understand the relationship of mold to substance. The means and methods under investigation were the casting process and, specifically, the tooling necessary for production. Geometric constraints influence issues of part removal and mold fabrication. Following casting, the part must be removed from the mold. This requires each part of the mold to avoid undercuts or geometric features that will lock the part to the mold. Molds are fabricated by CNC machining, hand sculpted, or cast over solid patterns. These forms of fabrication exert their own geometric pressure on mold design, which is explored through the work. Responsiveness was produced using two- dimensional, developable molds or reconfigurable three-dimensional molds in order to introduce material behavior and technology to the abstract, formal expression of the vessel.

Each proposal is a series of cast vessels made using one innovative mold, designed as a responsive machine for serial production. The projects argue for design processes that encourage robust feedback between digital technology and material tradition. Through these exchanges, new vessel forms are conceived and produced in series. Identical reproduction is replaced with non-uniform seriality.

Two projects used a *developable mold* for the rotational casting of urethane vessels. A developable mold is a three-dimensional mold capable of unfolding or flattening to a two-dimensional surface and reconfiguring in three dimensions again. The project 2:4:12 critically engages the bilateral symmetry of vessel forms, producing asymmetrical sidedness while maintaining the bilateral part line associated with two-part casting. Four developable molds were designed as flat patterns using garment making techniques. Each pattern features a particular boundary condition and internal features to regulate surface area and distribution. The two-dimensional patterns were fabricated with darts to dynamically modify the mold's surface area and alter the silhouette of each half independently. These darts were activated manually using individual zippers in order to reuse each form without producing identical casts and facilitate mold removal from undercuts. The four molds were paired to produce 12 different primary vessels (fig. 3). Individual refinements to the molds produced further variations in each half, thus expanding the series into larger families of vessel forms. The primary part lines of the two-part molds register on the exterior as sharp lines in contrast to the curvilinear expression of the soft undulation produced by darting on either side (fig. 4). The project's use of a developable, two-part mold is an exercise in sidedness. Rather than conceiving of the object as a rotationally or bilaterally symmetrical form, each vessel has two distinct sides. When presented in elevation, the object reads as unified, while from other vantage points, the object's articulated part lines join two juxtaposed silhouettes.

The project Dark Opulence designed one developable mold of tessellated equilateral triangles that included four possible, three-dimensional configurations within it. The triangular cells of the unfolded pattern were identical, allowing any edge to be matched to every edge within the pattern. Depending on the folding instructions used, the mold configuration differs in volume and silhouette, and the resulting cast vessel changes in form, orientation, and relationship to the surface on which it rests (figs. 4 and 5). The matched edges were fastened together on the exterior, producing hard edges where folding closed the mold and leaving soft edges where the tessellated forms were continuous. Each reconfiguration of the mold produced a fully closed silicone bag into which urethane was rotationally cast (fig. 6). The mold was tied into an external skeleton to prevent collapse during rotation. Further, the developed mold was coated with powdered pigments that produced a gradient hue of black to burgundy. As in 2:4:12, the final cast is cut to define its rim and opening, revealing the variable wall thickness that results from its mechanical casting process. Rotational casting allows the vessel to depart de-

cisively from the vertical axiality associated with thrown or cast vessels. The orientation of the vessel is not predetermined; rather, it emerges from the geometry and material distribution of each unique cast. A flat vessel base has been replaced by a series of sharp, distributed edges. These edges, a result of the reconfigurability of its mold, become the impossibly thin edges upon which the vessel delicately rests. Instead of determining an a priori vessel orientation, the vessel body settles into a relationship to the table that is dynamic, at once a factor of geometry and its specific center of gravity.

The next two projects explored the three-dimensional *reconfigurable mold*. In these projects, molds are produced in multiple parts that may be reoriented as individual parts or as an assembly. The first project, Tumble, explores orientation to both conform to, and undermine, production constraints. An eight-part mold is designed to tumble as an assembly, producing objects that refuse singular readings of orientation (fig. 7). Each mold part is machined from a different face such that when assembled, its tool paths and unique profiles purposefully misalign. While any given mold part complies with 3-axis machining limitations, the whole does not. These assembled rectangular molds are cut from the outside, producing a multifaceted polygonal whole. With the removal of one mold, porcelain slip is added to the remaining mold parts during casting. Reorientations of the mold are possible on each of its outside faces. The resulting series is similarly ungrounded (figs. 8 and 9). The artifacts of machining tumble around the vessel forms, making it difficult to relate these manufacturing side effects to a particular manufacturing process, or the vessel to a particular orientation.

The second project, Multibody, explores the mold as a kit of individual parts that may be assembled in numerous ways. The project challenges the unified expression associated with vessel bodies and the typical relationship of neck to vessel body. The vessel body is cut into quadrants. These quadrants receive a variety of mold parts and may stack up to three units high. The project treats the two resulting part lines as two independent faces that may or may not align. When the part line doubles and misaligns, the logic of mold assembly is directly expressed in the vessel. The stackable, reconfigurable parts challenge the dominance of the singular, rotationally symmetrical body of traditional vessel forms (fig. 10). The body of the vessel multiplies around its axis. As its parts are arrayed and reoriented, its silhouette is destabilized (fig. 11). Features start and stop abruptly, and the vessel's silhouette varies in the round. The body of each vessel bifurcates, multiplies, and separates, conflating body and neck and inside and out.

The last project, Static Variability, investigates fluid dynamics across a topographic surface with a specially designed one-part, open mold. The mold surface is

Figure 8: Vessel 2 of 5, Tumble

Figure 9: Vessel 5 of 5, Tumble

Figure 10: Vessel 2 of 8 and Vessel 1 of 8, Multibody

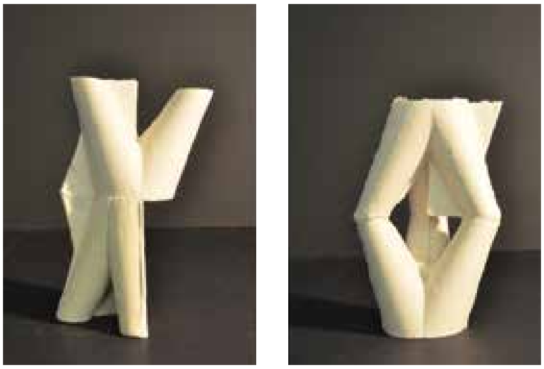

Figure 11: Vessel 6 of 8 and Vessel 3 of 8, Multibody

initially defined by a series of two-dimensional, closed contours that describe a field of nine concave chambers. These chambers are flexible units that produce a wide variety of vessel forms, featuring one or multiple aggregated units. The design ingenuity is in the relationship of these units, and the topographic surface in which they reside, to fluid dynamics. The design of the mold choreographs the flow of porcelain clip across the mold's surface, following multiple trajectories and originating at several fill origins (fig. 12). In slip casting, the flow of material may not stop during mold filling, or traces of this discontinuity remain in the vessel surface. Embracing this constraint, the mold was refined to channel fluids from unit to unit as the level of the slip rises. In addition, the contours are varied one above the next to produce flared rims at different levels of the mold. This allows vessels in the series to have a variety of depths, side wall inclinations, rim widths, and configurations (fig. 13). One-part, open molds typically result in simple vessel typologies such as platters, plates, bowls, or cups. By studying the geometric definitions of body and rim, this project incorporates the potential for many vessel forms in one ingenious mold. Nearly 30 vessels of varying size, shape, and configuration were made in order to argue for the mold as a site of design research.

This body of work attempts to make the case that high and low technologies, when carefully and thoughtfully combined, not only escape the aesthetic limitations of individual tools but also support robust material experiments. When adopting an agnostic rather than technophilic or positivist relationship to technology, one can visit problems of design with new sensibilities and more comprehensive expertise. As noted by Moma's Senior Curator of Architecture and Design Paola Antonelli in the exhibition catalog *Mutant Materials*, "Today, very high technology can coexist in peaceful synergy with very low technology."[3] Contemporary technology and the technologies of craft, taken together, afford a plasticity to objects that allows us to revisit the conventions of design, establishing new relationships between part and whole, one and many, and the object and ourselves.

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IMAGE CREDITS

All project images are credited to respective students (see below), except for Figure 1, credited to Roberge, Heather.

STUDENT WORK

2:4:12 by Ciro Dimson, Angel Gonzalez, and Camella DaEun Kim

Dark Opulence by Fuk Man (Fei) Mui, Kara Moore, and Alex Rickett

Tumble by Andrew Akins, Miguel Nobrega, and Emma Price

Multibody by John Brumley, Sarah Johnson, and Corliss Ng

Static Variability by Julieta Gil, Jazzy Lin, and Jeff Rauch

DESIGN SEMINAR CREDITS

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Figure 12: One-Part Topographic Mold, Static Variability

Figure 13: Vessel Prototypes, Static Variability

Twisted: Literal & Phenomenal

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Twist: To form (something) into a particular shape by taking hold of one or both ends and turning them; Turn or bend into a specified position or in a specified direction; To move one's body so that the shoulders and hips are facing in different directions; Cause to rotate around something that remains stationary; To wring or wrench so as to dislocate or distort; To alter the meaning of: pervert; To cause to take on moral, mental, or emotional deformity.

'Turn,' 'bend,' 'distort,' 'pervert.' These terms are but some of the ones selected from definitions of the word twist found in the Oxford and Merriam-Webster dictionaries. "The French translations are: *tordre, torquere*. Torquere (similar to the English torque/torsion) means to turn, to turn around, to torture. The association with the notion of torture is particularly interesting: tying up and strangling with a powerful and unavoidable turn enlivens the image of twisting."[1] 'Turn' and 'bend' describe a benign mechanical action. 'Distort' and 'pervert' suggest something more adverse. In contemporary architectural parlance, both are favorable, as they belong to a lineage of motion[2] on one hand and dislocation[3] on the other. But twisting is a specific kind of bending/distortion that has all but been exhausted in the past two decades of architectural production. Examples abound worldwide and at various scales, and not for unwarranted reasons. A simple twist to a material, form, or body can yield powerful effects. The dance craze "the twist" became an overnight sensation throughout the U.S. and Europe when, in one summer of the late 1950s, Chubby Checker performed it on Dick Clark's "American Bandstand."[4] The main part of its appeal to teens and young adults is that it *perverted* what was considered socially acceptable movement between male and female: the gyrating and twisting action of the body on the dance floor suggested sexual activity and desire, *which dislocated the metaphysic of dancing*. In architecture, a specific kind of dislocation occurs in relation to twisting, and a qualitative distinction must be made between an actual or *literal* and an apparent or *phenomenal* twist.

First, let's try to pin down a more specific material[5] definition of each as they might pertain to architecture. Literal twisting is the *deformation of a generic substance/material through opposing rotation at its ends along an axis perpendicular to those ends*. Phenomenal twisting is *the appearance of such achieved by other means of for-*

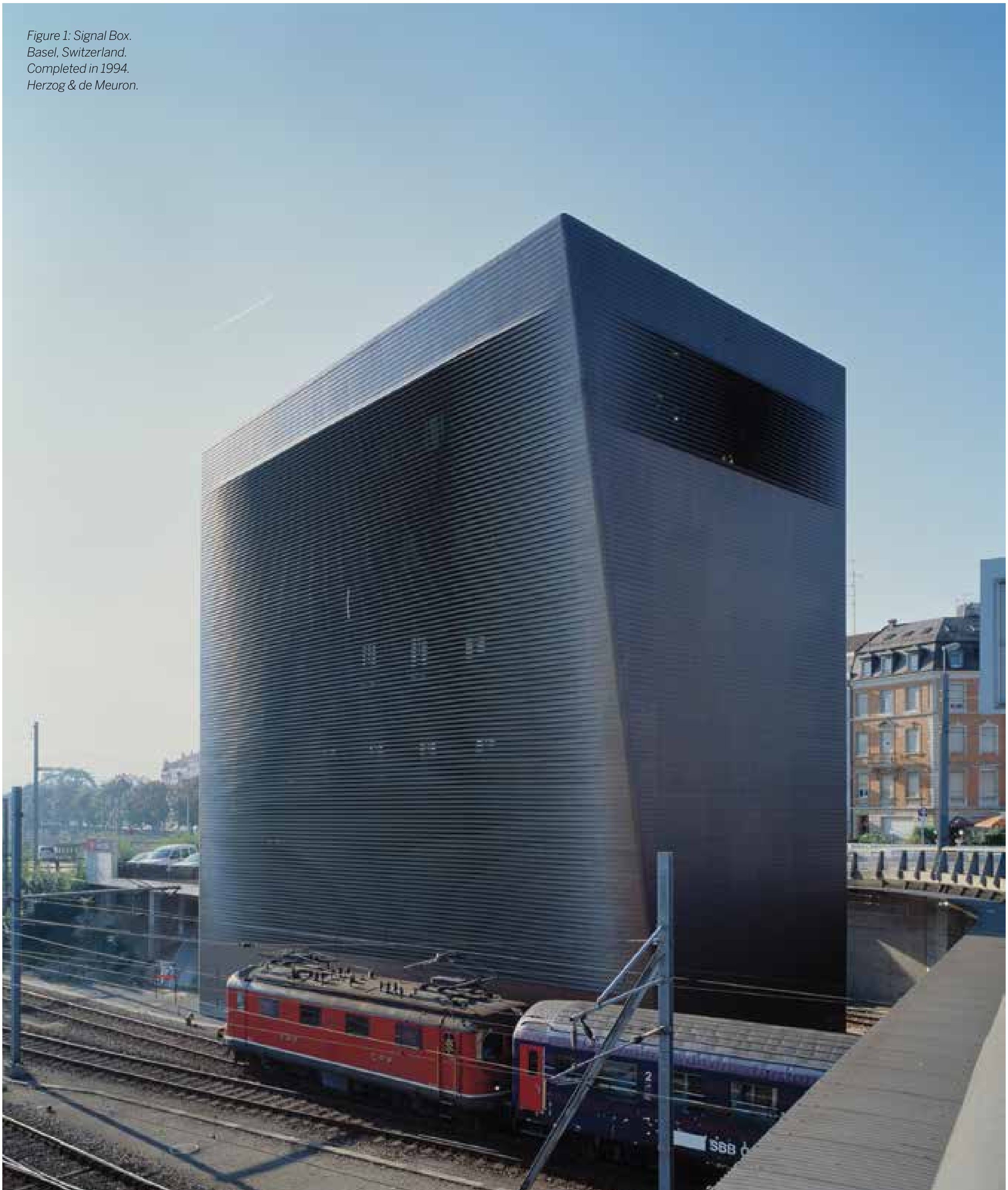


Figure 1: Signal Box.
Basel, Switzerland.
Completed in 1994.
Herzog & de Meuron.

mation. The key terms of distinction being *deformation* in the former and formation in the latter, foregoing any implication as to one being real and the other being a mere appearance.[6] They are both considered equally real. In the philosophical genre of phenomenology, the doctrine of intentionality claims: "There are no 'mere' appearances, and nothing is 'just' an appearance. Appearances are real; they belong to being. Things do show up....Things that had been declared to be merely psychological are now found to be ontological, part of the being of things."[7] In Jeffrey Kipnis' essay on the Nelson-Atkins Museum of Art in Kansas City by Steven Holl entitled "...and Then, Something Magical," he takes a brief detour to distinguish between two models of existential phenomenology as it applies to architecture in relation to technology: Heideggerian vs. Merleau-Pontyan. In short, the Heideggerrian model associates appearances and technology with inauthenticity, whereas: "Merleau-Ponty rejects his colleague's position that meaning and authenticity arise from a metaphysical relationship between appearances and being, preferring to inquire how these evolve from perceptions of a body living in a world as phenomena. To ground his discourse thoroughly in perceptions, he discusses the interplay of things, experiences, and ideas in terms of the *visible* and *invisible*, emphasizing the way these two interact with and change each other, calling attention to what he calls the 'profound carnality of their doubling.'"[8] In terms of effects, isn't this precisely what twisting does: produce an oscillation between the visible and invisible parts of a surface/form? Doesn't twisting provide a *doubling*, or the simultaneity of turning away from and toward another object (be it a viewing subject, another building, geographic orientation, etc.)? Isn't this the core of its power and why it has gained such popularity and become so ubiquitous over these past two decades? Along with these performative effects of twisting, the ushering in of the digital era of the early 1990s and an aggressive interest in topology also greatly contributed to its popularity. To be sure, we must catalog the various scales at which the twisting effect occurs and the qualitative and quantitative differences between them.

Twisting in architecture can be categorized into three scales: the *material component* (small), *massing moments* (medium), and the *whole mass* (large). An abundance of great examples abound, both built and speculative, but I have selected only one or two built ones for each category that I find most clearly demonstrate the differences and effects set out by the paper's framework. At the material component scale, we typically find strips or slats of sheet material (metals, wood, plastics, etc.) and usually in large numbers. This scale requires small parts and lots of them (hundreds and thousands) and begins with the literal twisting of a basic strip of material. The phenomenal effects achieved are delivered at a larger scale when a critical mass of twisted strips yields field effects such as moiré patterns. In the better cases, a dematerialization of a larger surface occurs where the accumulated twisting of the strips reveals something akin to an apparition of the thing it is enveloping. It produces atmospheric effects. A prime example of this is Herzog & De Meuron's Signal Box in Basel, Switzerland, completed in 1994 (fig. 1), which is wrapped in horizontal strips of copper at 17.50 cm wide that twist from zero degrees (flat and closed) to 60 degrees from negative z (fig. 2).[9] While the conventions of frontality and facade are maintained, continuity occurs in both the surgical handling of assembly and a small fillet rounding off the corners. The limitation of the twisting from zero to 60 degrees is one imposed by material and methodological constraints. The twisting occurs gradually over a long enough span not requiring mechanical means of deformation. It is simply a byproduct of connecting the strips to gussets at evenly spaced and variably angled intervals. But the limitation also contributes to the apparition-like qualities: by not twisting to a full 90 degrees, the conventional interior is never fully revealed when viewed frontally. This also privileges viewing it from the ground at a specified distance in order to receive maximum (but never full) exposure of what lies beyond. Twisting a planar and rectilinear strip of material beyond a certain angle threshold would result in the distortion of the material into a new figure and requires advanced means of formation vis-à-vis computation. Arguably, the Signal Box project serves as a contemporary canon for twisted effects found in digitally generated architecture. Ironically, the project was achieved through analog means, right at the cusp of the digital era.

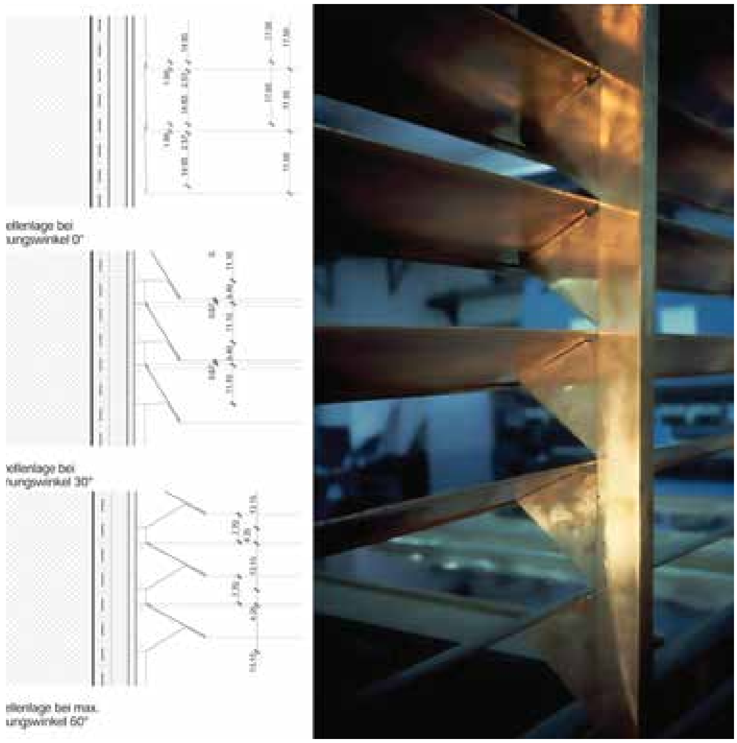


Figure 2: Details and mock-up of angled support intervals.

Figure 3: (Left) Leaning Satyr, c. 130 AD. Roman copy of sculpture by Praxiteles, c. 4th century BC (Right) Venus de Milo by Alexandros of Antioch, c. 130–100 BC.

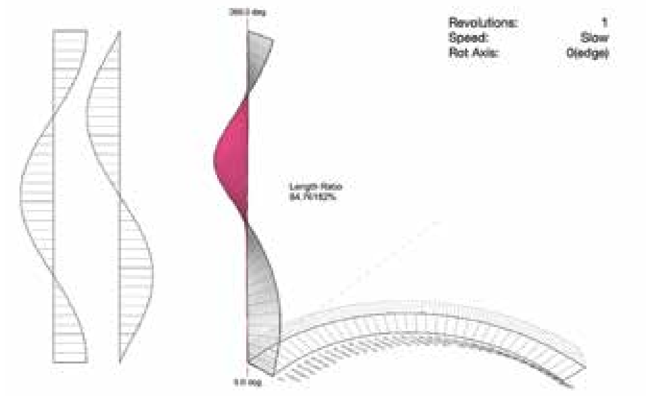
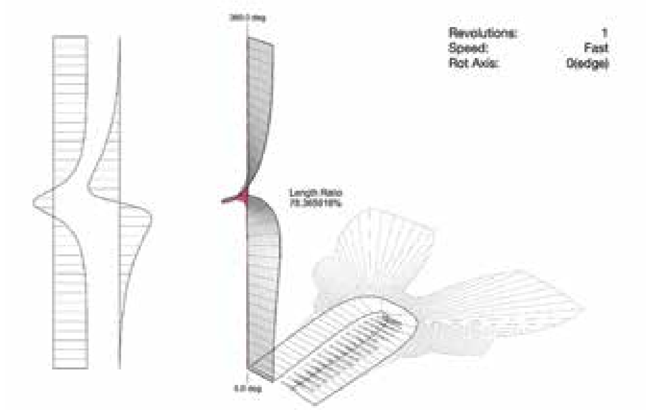


Figure 4: (Left) Replica of David by Michelangelo, c. 1500. (Right) David by Bernini. 1623.



Moving on to the middle scale, we find a shift in effects and material logic. Massing moments of twisting are found when a project employs the twisted surface at a scale larger than the material component but not as one large move of a single mass. It is a means to simultaneously break down a building's massing yet maintain coherence through surface and spatial continuity. While twisting at the scale of the material component focuses all of its energy on surface (perceptual) effects, this middle scale of twisting enters into organizational territory: the scale of the twisting action moves space around. At the small scale, the twisting effect is directed at the eye. At the middle scale, it is directed toward the body. It exchanges deformation of material for deformation of massing geometry and can be constructed out of an undistorted planar sheet logic, a modular unit (brick), or a mold (cast-in-place concrete).

A clear example of the latter is Miguel Fisac's Jorba Laboratory, located just outside of Madrid, Spain, and built in 1968. A seven-story tower of repetitively stacked floor plates is distorted by rotating the alternate ones 45 degrees in plan. The rotation is interpolated by twisted surfaces made of cast-in-place concrete. The overall mass is broken down into constituent parts (as floor volumes) yet made continuous through the twisted surfaces. The eye is invited to wander in rhythmic undulation, from any stationary vantage point, from base to top. But more importantly, the body is invited to move around the building to receive alternating compositions of the stacking as it snaps into alignment every 45 degrees: a double

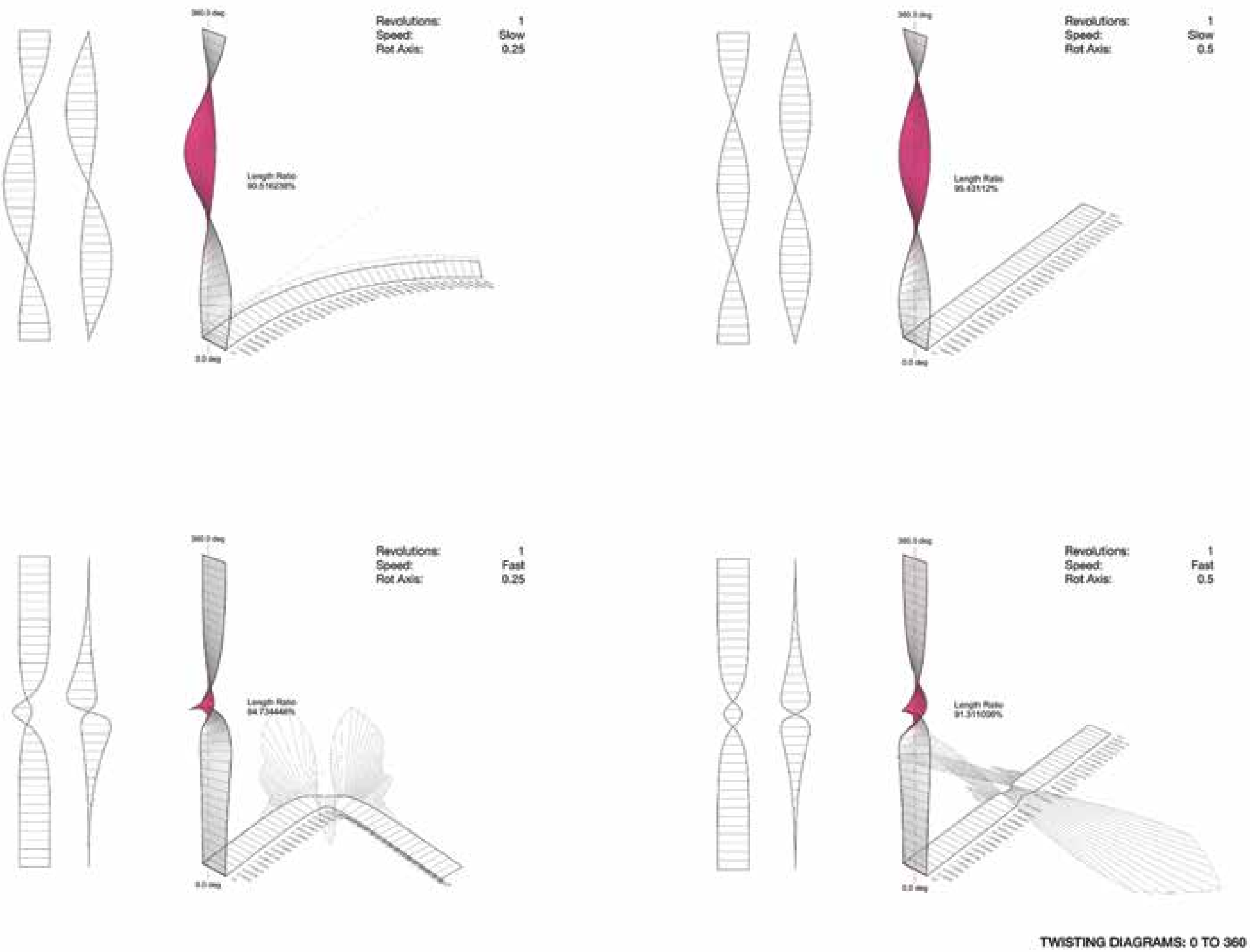


Figure 5: Twisting Diagrams

sense of frontality where "whole units of space are put into motion."[10] In this case, the twisted element is revealed as an index of the form-work, and one can identify the panel seams located at ¼ intervals along each edge of a face. The literal twisted unit of construction appears to be modular and repeated, with each half being composed of two inversions of the ¼ unit. This legibility gives way to an understanding of the analogical sequence, thus the lack of need for computational intervention.

A more idiosyncratic version of this, dependent on computational intervention, is Preston Scott Cohen's Herta and Paul Amir Building in Tel Aviv, Israel, completed in 2011. The twisted effect operates at a similar scale to Fisac's example but is of a different tectonic logic and contains variable resolutions of twisting. In this case, rotation of the stacked volumes is neither repeated nor adheres to regular angle intervals. Rather than a doubling of the expression of two clear orientations, the building's tension lies in the simultaneous desire of the massing to maintain a sense of frontality while being distorted into something other than. This kind of turning away is continuously wrapping around and oscillating from ground to mid-section to roofline, pulling the viewer's eyes and body sometimes in conflicting directions. The tectonic logic of the panels, a blend of large triangulated and quadrangulated planar pieces, indexes which faces of the mass are normal and which are twisted. Each of the twisted surfaces is variably subdivided, with the panel seams almost always continuous with those of the normal surfaces. The twisting moments of the massing

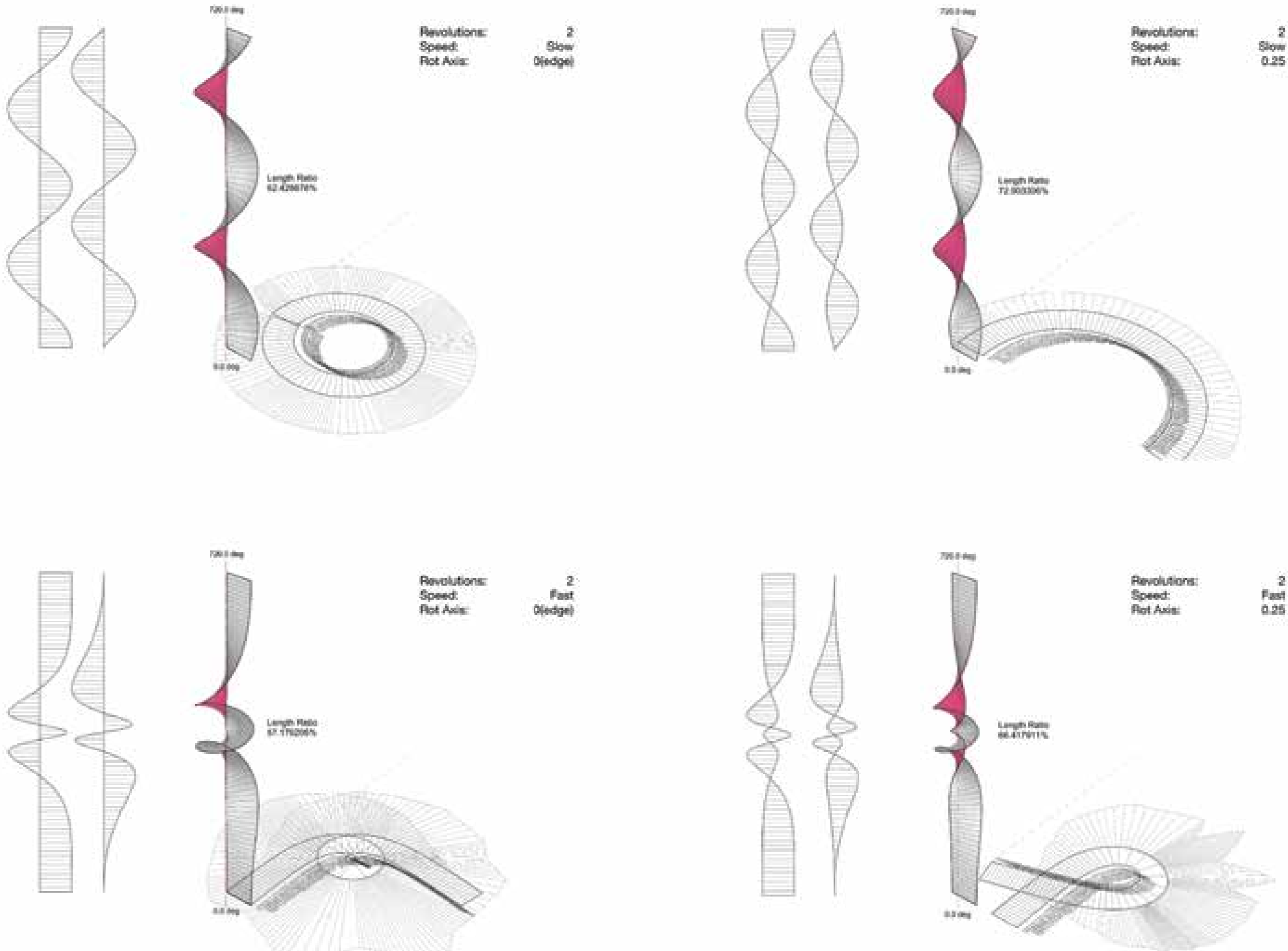
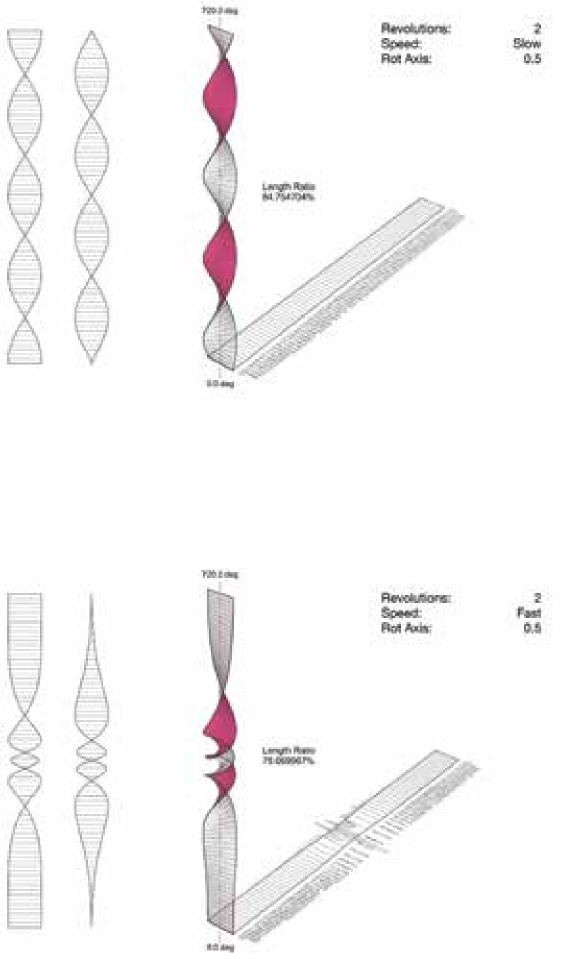


Figure 6: Twisting Diagrams

pulls the body in, out, and around, dislocating the notion of a privileged position.

At the large scale, that of the single twisted object, we again find a shift in effects from the previous two, but often a shared tectonic logic of the middle one. This scale is best exemplified in the typology of the tower and is probably the most global, due to its ability and ease in achieving iconic status. The problem with the examples at this scale is that they tend to be either large caricatures of the small scale but in singular form, or simply metaphors of bodies in motion.[11] A case in point is the Turning Torso (an explicit adherence to the body metaphor) by Santiago Calatrava, located in Malmo, Sweden, and completed in 2005. Inspired by a similar sculpture by the architect that is supposed to resemble



TWISTING DIAGRAMS: 0 TO 720

a twisting human spine, the residential tower twists a full 90 degrees from base to top and is comprised of nine pentagonally-shaped stacked volumes. It certainly achieves a confounding of frontality and a simultaneity of turning away from and toward a viewing subject. But at this scale, it doesn't seem enough. The added feature of an exoskeleton, where the structure is exposed on two of the five faces, incurs an inflection in the envelope (where the other sides slightly bulge outward), and adds a bit more drama to the story. In this example there is the phenomenal twisting at the large scale but also a literal twisting at the component scale. The aluminum skin panels are actually twisted, which does contribute to the smoothness of the overall twist, save for the two-meter deep gaps every sixth floor.

A similar project, but of a more modest scale and expression, is the Gehry Tower in Hanover, Germany, by Frank Gehry, built in 2001, Rather than being an isolated object, this nine-story building is situated at the corner of an urban block. The rotation from base to top is limited to approximately 20 degrees. This subtlety of twisting is less about confounding facade orientations and more about the mass gently turning about to find its comfort zone. It is more of a suggested turning away than a full-fledged one. Similar to the Turning Torso (at the non-exoskeleton sides), the exposed faces of the Gehry Tower have a slight bulge to them, and the skin panels are comprised of curved metal, stainless steel in this case. The site constraint, paired with the subtle handling of the mass, seems to be productive in regards to the twisted object-building: it replaces the ambitions of iconicity with one of posture and character, which is more of an "aw-shucks" presence than one announcing, "Here I am."

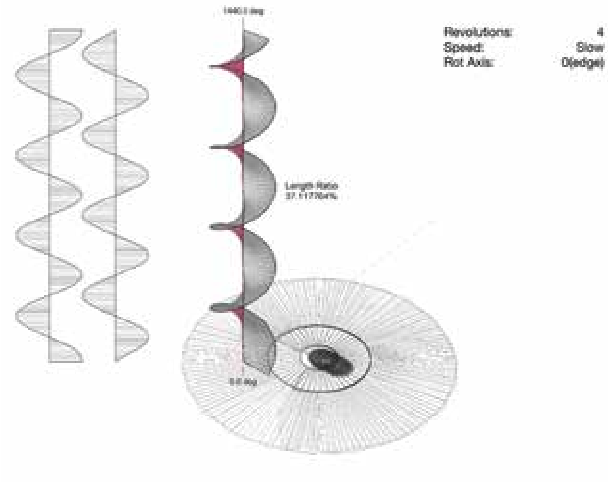
To expand on this notion of posture and character in relation to twisting, we can turn to the Classical and Renaissance sculpture of the human figure.[12] Contrapposto, which means counter-posture, or counter-balance, in Italian, was a Classical (Greek antiquity) sculptural effect revived during the Renaissance. It dealt with the problem of how to distribute the weight of the body in a seemingly natural way that affected a psychological disposition. In contrast to the S Curve, which involves more of the body and idealizes it into a sinuous S shape, Contrapposto was used to produce tension in the figure between a relaxed and dynamic posture. Sometimes the distinction is subtle. The key element in contrapposto is that the "human figure is standing with most of its weight on one foot so that its shoulders and arms twist off-axis from the hips and legs."[13] An example of this subtle distinction can be found in two Classical sculptures a few centuries apart: the Leaning Satyr and the Venus de Milo (fig.3). The former is vaguely both an S Curve and contrapposto, although not elegantly either. We can draw and locate an S Curve from head to toe, but it is merely frontal. And we can see that most of the weight is distributed to the left foot, until we account for the tree branch that the figure is "leaning" against. It is as if the figure is flaunting its indifference to either principle. The Venus de Milo on the other hand displays the quintessential S Curve, where the whole figure, from central axis to silhouette, is tuned to the sinuous shape. A subtle twist can be detected between the orientation of the legs to that of the torso and head, an elegant composition but lacking in any affect or disposition.

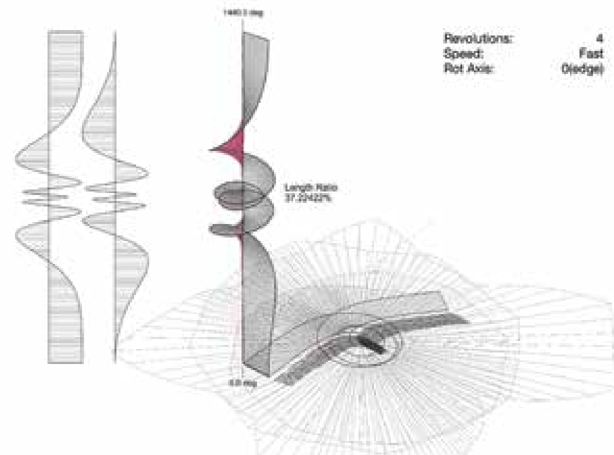
Just over a century apart, two versions of the statue of David represent the height of Renaissance and Baroque sculpture: Michelangelo's and Bernini's, respectively (fig. 4). In the version from the former, we have quintessential contrapposto: the body's weight focused on the right foot; the left foot and leg slightly relaxed and forward; a twist at the neck turning the head away from the body's frontal orientation; and the overall tension of a psychological disposition between conscious decision and action.[14] Bernini dislocates the metaphysic of contrapposto by first deciding to depict David in the throes of action. The entire body is contorted into a more complicated twist, where the arms and torso are twisted against the frontality of the head and legs. The tension is more physical and immediate, compounded by the coiling drapery through the groin and around the waist. It should be noted that the scale difference in the image is no accident. Michelangelo's David is larger than life, standing at 17 feet tall, while Bernini's is human scale. The scalar and postural differences account for another set of effects related to distance. The former's is intended to be observed at a distance, occupying its own mental and physical space. The latter's is intended to occupy the space of the viewer, to collapse any sense of distance, producing an intimacy. In all cases, a phenomenal twisting (of the body) is achieved in the formation of stone through the tools of chisel and hand.

Early examples of literal twisting in architecture and related practices can be found in medieval metalsmithing. From cutlery to weapons to ornamental grilles, twisted iron has a long tradition of at least accessorizing our environment. And despite the stigma of the lack of other forms of progress during the Middle Ages, iron manufacture and the three interrelated practices of mining, smelting, and smithing made significant advances during this time. The blast furnace and the application of waterpower are two important technological advances made in this period. "The blast furnace used waterpower to increase draft and, therefore, temperature, allowing iron to be smelted much faster, cheaper, and with the option of creating cast or wrought iron."[15] Steel is the combination of both cast and wrought iron with small amounts (1% or so) of carbon. The wrought variety (wrought, from "wreak": to bend or twist) is a soft and ductile version and is closest to pure iron. It can be easily worked and bent into various forms but loses its sharpness easily and is only moderately strong. The cast variety comes out of the smelter in liquid form and is poured into molds not unlike bronze. It makes up for the former's lack of strength but is very brittle and will crack if worked over, even at high temperatures. So the twisting of iron is limited to its wrought form.

There was an array of implements used to twist wrought iron, from small hand-held tools to larger machines. One such device was used to produce numerous and continuous twists, or rotations, from end to end of flat stock material or bars. Another kind was used to make half-turns of flat stock where the twisting action occurs within a variable span of material.

This device raises the issue of the mechanics involved





in the literal twisting of generic materials, such as strips and bars. In this case, great force (torture?) is required to twist a relatively small flat metal bar at least one full revolution (but often times several) of 360 degrees. In contemporary architecture, we rarely see this degree and type of twisting. Moreover, given the role of computation, the literal twisting of flat stock material has given way to a literal twisting of geometric surfaces, which are sometimes also referred to as ruled, scroll, or developable, which are then unrolled into flat shapes for fabrication to produce phenomenal effects. The primary difference between a ruled and developable surface is that developable surfaces can be unrolled without deformation (stretching) while the same is not always true of the former. Most developable surfaces are ruled, with the

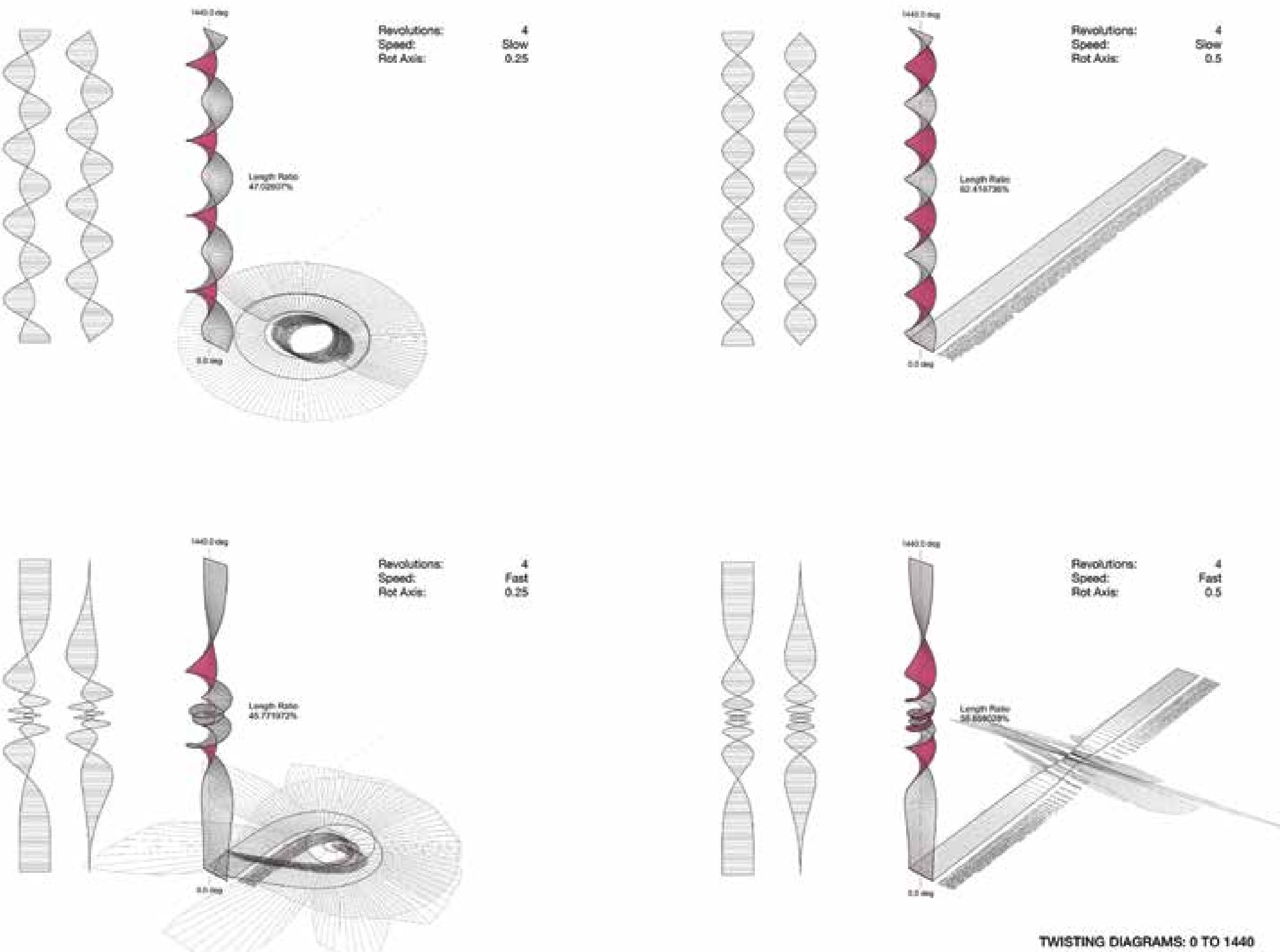


Figure 7: Twisting Diagrams

exception of those embedded within four dimensions.[16]

There are various definitions of ruled surfaces depending on which branch of geometry is being referred to. Wikipedia offers a clear definition that is taken from the publication *Compact Complex Surfaces*:

> *In geometry, a surface S is ruled (also called a scroll) if through every point of S there is a straight line that lies on S. The most familiar examples are the plane and the curved surface of a cylinder or cone. Other examples are a conical surface with elliptical directrix, the right conoid, the helicoid, and the tangent developable of a smooth curve in space. A ruled surface can always be described (at least locally) as the set of points swept by a moving straight line. For example,*

a cone is formed by keeping one point of a line fixed whilst moving another point along a circle. A surface is doubly ruled if through every one of its points there are two distinct lines that lie on the surface. The hyperbolic paraboloid and the hyperboloid of one sheet are doubly ruled surfaces. The plane is the only surface which contains at least three distinct lines through each of its points.[17]

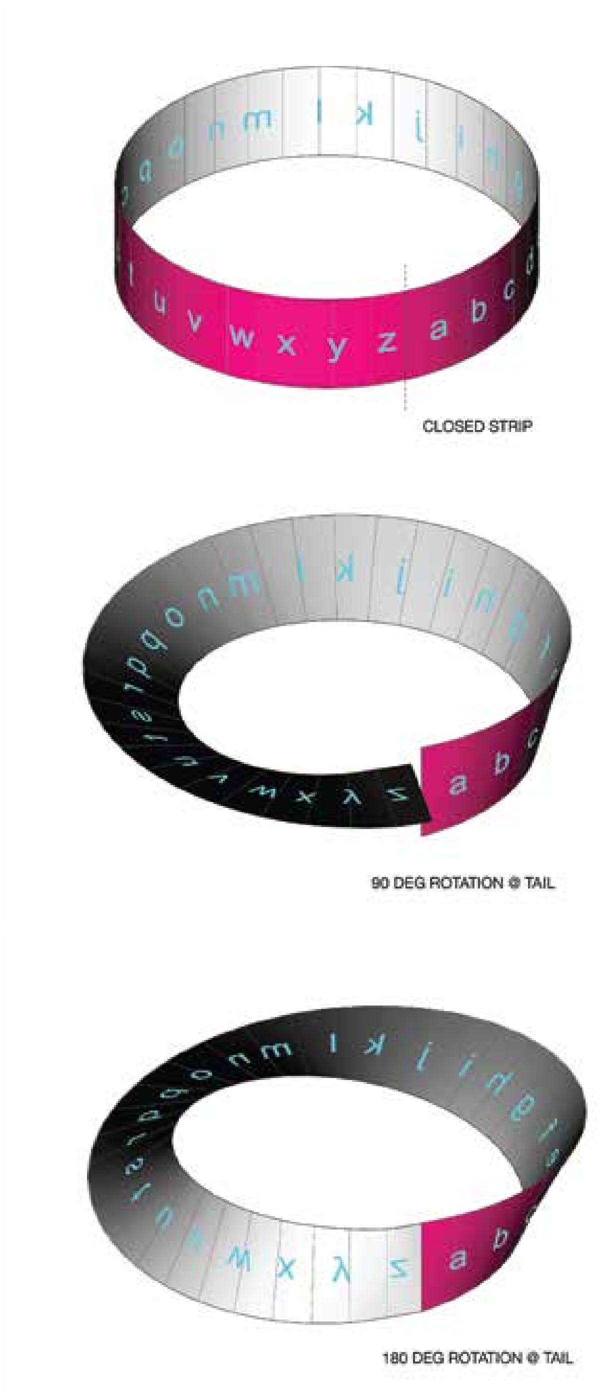


Figure 8: Mobius sequence from two-sided ring

A series of diagrams (figs. 5–7) attempt to geometrically simulate the variable twisting (torturing) of a surface strip to visualize the relationship between a ruled surface in three dimensions, its unrolled (flattened) projection in two dimensions, and the degree of deformation between the two.

Each set of diagrams corresponds to three different numbers of revolutions occurring from base to top: one (360 degrees), two (720 degrees), and four (1440 degrees). Each diagram is organized vertically according to speeds of twisting (slow on the top, fast on the bottom). These speeds refer to the vertical distribution of rotation angles per strip. Horizontally, the variable is the location of the rotation axis: justified to one edge; 25% along the edge; and the midpoint. The strip is shown in axonometric with the colored region indicating the back face. Projected in XY is the unrolled version of each showing the flat shape required to produce the twisted strip in question. The faint erratic set of lines is the curvature graph of the unrolled strips, which graphically indicates the degree of deformation occurring. To the left of the axon strip are the front and side views, respectively, orthographically projected to the picture plane. The "Length Ratio" number indicates the ratio of the longest unfolded edge length to the length of the strip.

While this is not a major revelation or a one-to-one correspondence of geometry to matter, it does reveal that even in the least torturous version (360, slow, 0.5 axis) there is some deformation, consistent with that of material behavior. It also shows the impossibility of some of these to be materialized as a single uninterrupted piece of material. The unrolled projections that fold (intersect) onto themselves would have to be rationalized into parts, thereby foregoing deformation (literal) techniques and requiring other means of formation to produce phenomenal twisting (like most in the tower genre). The ones that don't intersect themselves could be considered absolute twists, where a literal twisting of material produces phenomenal twisting effects.

To make the case for the role of topology in the contemporary obsession with twisted surfaces, we need look no further than the Mobius strip, probably the most referenced topological model in architecture's recent history. But before getting into the specifics of the Mobius, some background on topology's gen-

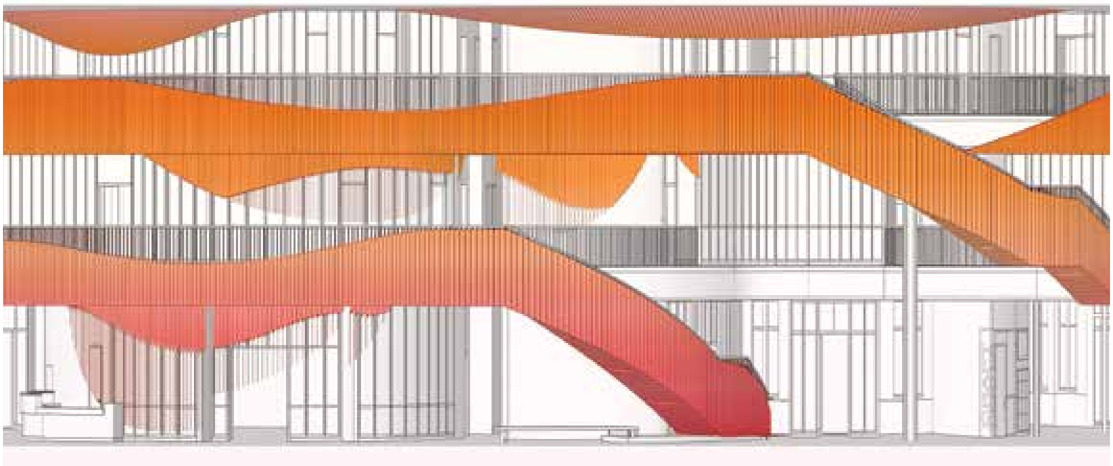


Figure 9: Afterglow: unrolled interior perspective elevation

eral appearance in architecture is in order. There is a distinction between topology as a branch of mathematics and how it is used/understood in architecture. For hardcore mathematicians, topology should not be visualized in images because it reduces the equations they represent to caricatures. Because topology deals with certain kinds of shapes and spaces, architecture has relied on precisely those images that mathematicians try to avoid. In a general sense, topology is the study of continuity. More specifically, "A topologist is interested in those properties of a thing that, while they are in a sense geometrical, are the most permanent—the ones that will survive stretching and distortion."[18] This provides the reason why a torus (donut) can become a coffee cup and why a square is no different than a circle, as long as the sequence of points defining the curve is maintained.

The desire for continuity was part of a broader agenda, articulated in *Folding in Architecture*, the canonical publication edited by Greg Lynn in 1993, for moving past the conflict-and-contradiction values of deconstructivism. In the 2004 revised edition, Mario Carpo succinctly sums up the goal of folding: "Folding is a process, not a product; it does not necessarily produce visible folds (although it would later on); it is about creating built forms, necessarily motionless, which can nevertheless induce the perception of *motion* by suggesting the 'continual variation' and 'perpetual development' of a 'form becoming'...." Eisenman himself, at this early stage in the history of folding, defined it as a 'strategy for dislocating vision.' In an essay published the same year by Greg Lynn, he states: "Deconstructivism theorized the world as a site of differences in order that architecture could represent these contradictions in form. This contradictory logic is beginning to soften in order to exploit more fully the particularities of urban and cultural contexts. This is a reasonable transition, as the Deconstructivists originated their projects with the internal discontinuities they uncovered within buildings and sites. These same architects are beginning

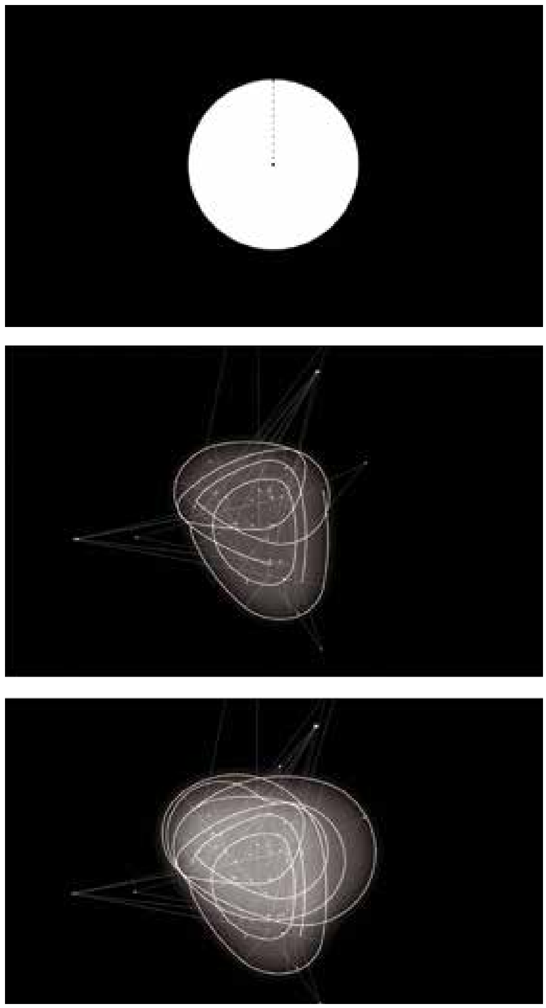


Figure 10: Afterglow: plan diagrams

to employ urban strategies which exploit discontinuities, not by representing them in formal collisions, but by affiliating them with one another through *continuous* flexible systems."[19] This theoretical position paved the way for topology as a diagrammatic and morphological instigator in the smoothing of architectural form. A set of terms/operations born out of this discourse of continuity set the stage not only for advancing techniques for practitioners but also for pedagogy: bending, twisting, pleating, braiding, knotting, weaving, etc.

The Mobius strip, as a diagram, clearly illustrates the power of this brand of continuity. As a surface object, it confounds the notion of sidedness: it is a single-sided surface where inward and outward facing moments are within a continuous system of exchange. As a spatial object, it confounds the notion of interiority/exteriority: space moves continuously and seamlessly between the two. This diagram represented a holy grail of sorts for those seeking a new sense of political freedom associated with spatial and surface effects. Technically speaking, there are a number of ways to produce a Mobius strip. You can take a flat and straightened strip of material or geometry, twist it 180 degrees, then connect the ends, or you can start with a strip as a ring, splice it, twist one end, then reconnect it. As a sequence, the former example violates the principles of topology since what started as disconnected ends in a connection. The latter example complies with topology since it begins connected, gets disconnected, and is then reconnected: the original and final conditions match. For architecture, this dogmatic approach was irrelevant. What mattered was the final result, no matter how it was achieved.

Figure 8 illustrates the latter example and actually reveals the contradiction of continuity/discontinuity when seen as a generative sequence. If we disregard the color and notational codification, then we do have a single-sided continuous surface. But if we account for the operational sequence, then its two-sidedness is revealed in the color-coding of each side as well as the orientation in the lettering sequence. In its Mobius form, one end is upside down in relation to the other. Maybe this is less a contradiction and more an ambivalence: simultaneously having it both ways. Or, more precisely, perhaps it is the difference between a literal and phenomenal Mobius, with architecture heavily privileging the latter. Since a literal Mobius has already been rejected as a possibility by mathematicians of the highest ranks, then architecture could only contend with either the appearance of one, or, more productively, treating it as a primitive that undergoes further transformation as it absorbs increasing amounts of information (i.e., site constraints, structure, program, circulation, ornament, etc.).

A case study will now be used as an example of a minor lateral advancement (as opposed to a major vertical advancement) of phenomenal twisting at the material component scale. It is a project entitled *Afterglow*[20]

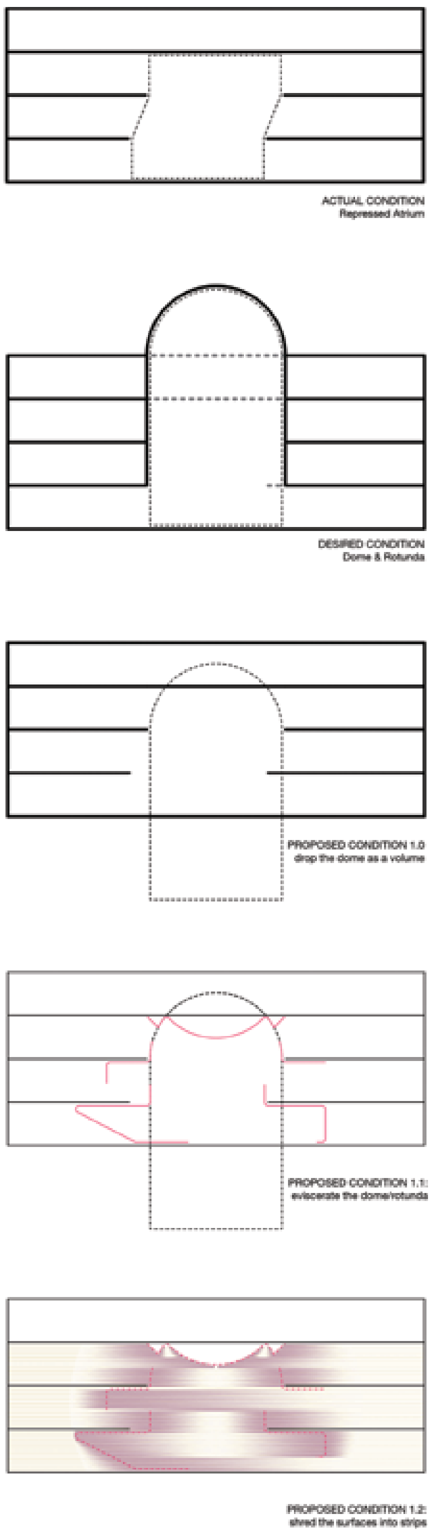
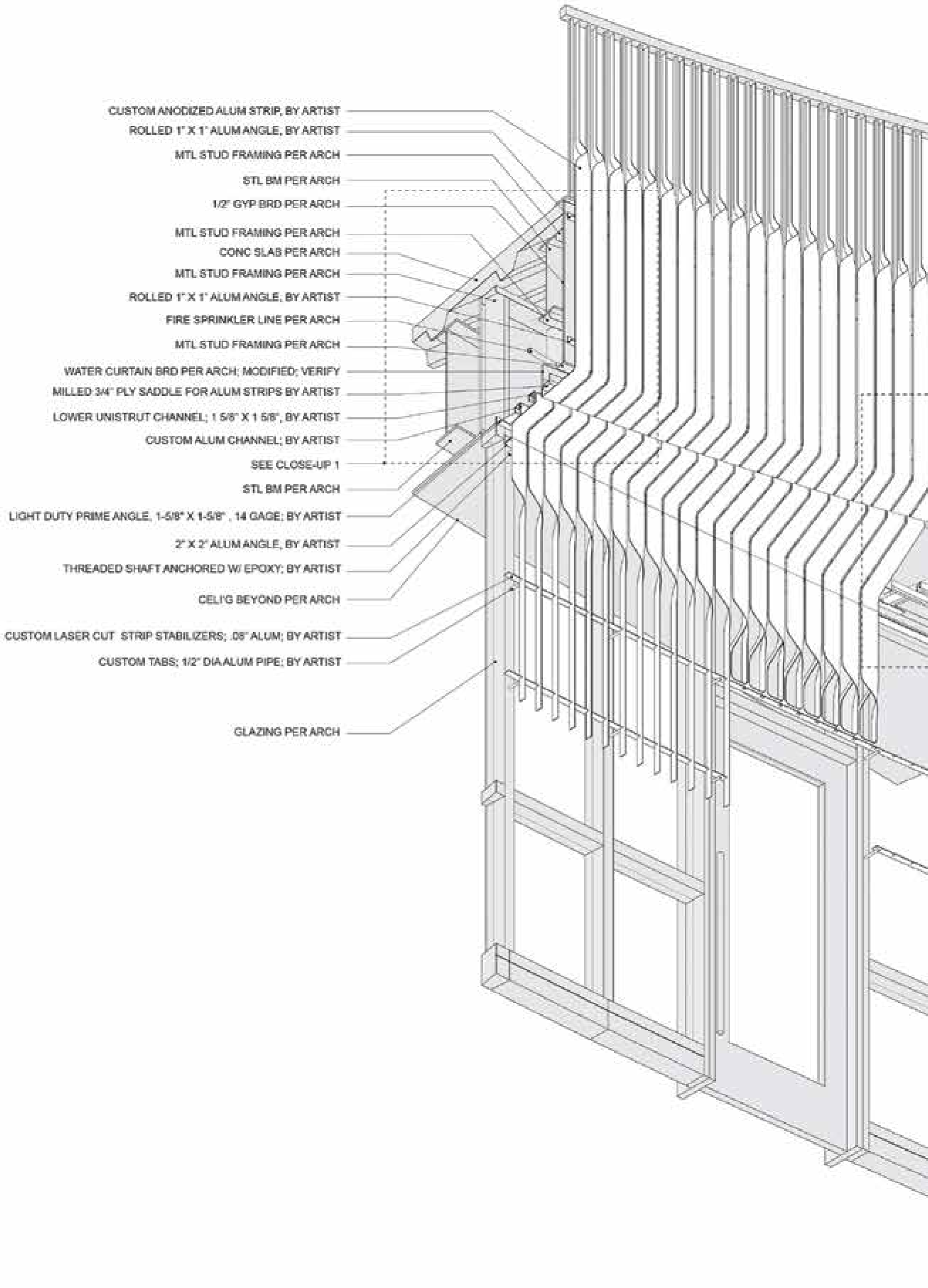


Figure 11: Afterglow: section diagrams

Figure 12: Afterglow: worms-eye oblique


CUSTOM ANODIZED ALUM STRIP, BY ARTIST
ROLLED 1" X 1" ALUM ANGLE, BY ARTIST
MTL STUD FRAMING PER ARCH
STL BM PER ARCH
1/2" GYP BRD PER ARCH
MTL STUD FRAMING PER ARCH
CONC SLAB PER ARCH
MTL STUD FRAMING PER ARCH
ROLLED 1" X 1" ALUM ANGLE, BY ARTIST
FIRE SPRINKLER LINE PER ARCH
MTL STUD FRAMING PER ARCH
WATER CURTAIN BRD PER ARCH; MODIFIED; VERIFY
MILLED 3/4" PLY SADDLE FOR ALUM STRIPS BY ARTIST
LOWER UNISTRUT CHANNEL; 1 5/8" X 1 5/8", BY ARTIST
CUSTOM ALUM CHANNEL; BY ARTIST
SEE CLOSE-UP 1
STL BM PER ARCH
LIGHT DUTY PRIME ANGLE, 1-5/8" X 1-5/8" , 14 GAGE; BY ARTIST
2" X 2" ALUM ANGLE, BY ARTIST
THREADED SHAFT ANCHORED W/ EPOXY; BY ARTIST
CELI'G BEYOND PER ARCH
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CUSTOM TABS; 1/2" DIA ALUM PIPE; BY ARTIST
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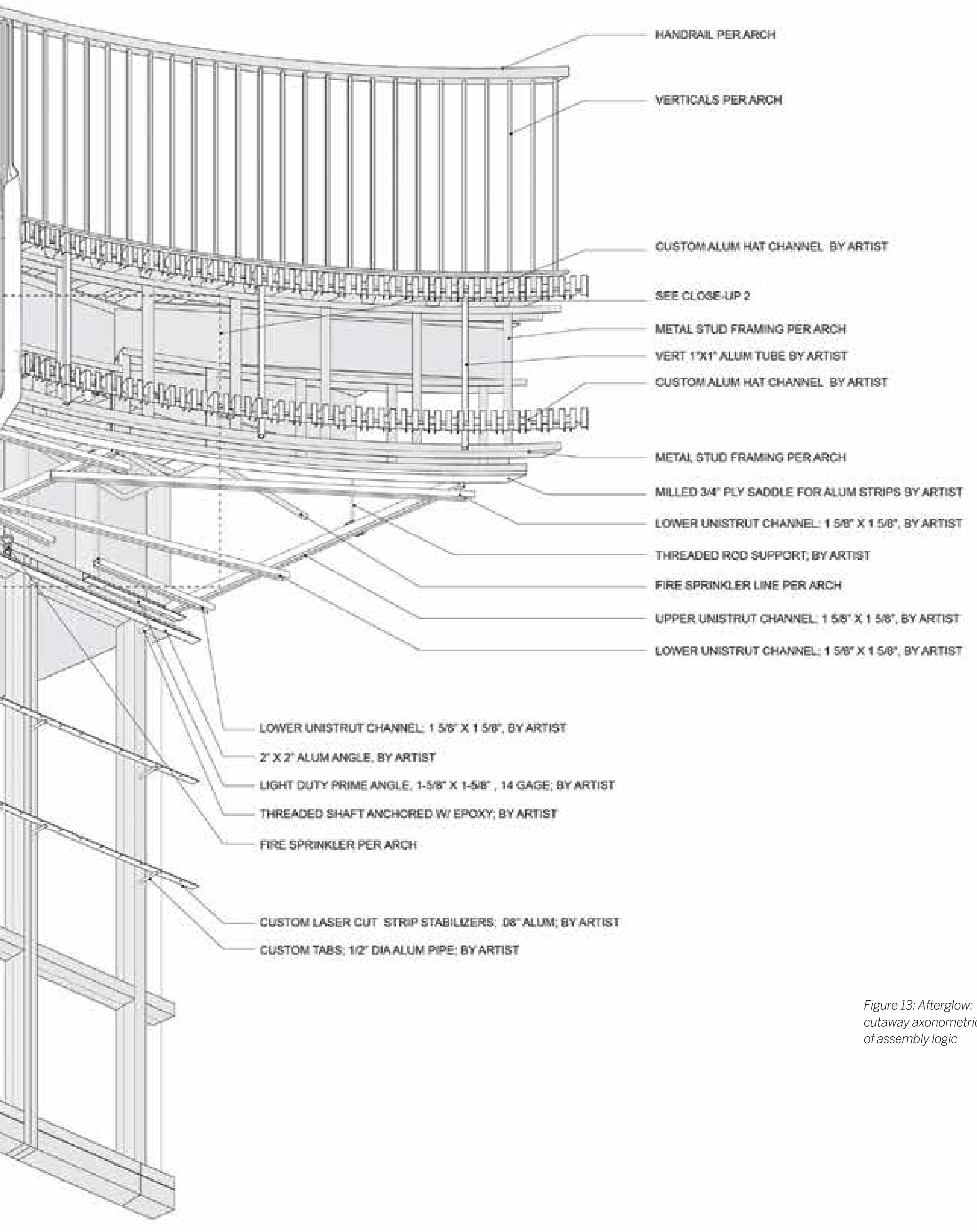


Figure 13: Afterglow: cutaway axonometric of assembly logic

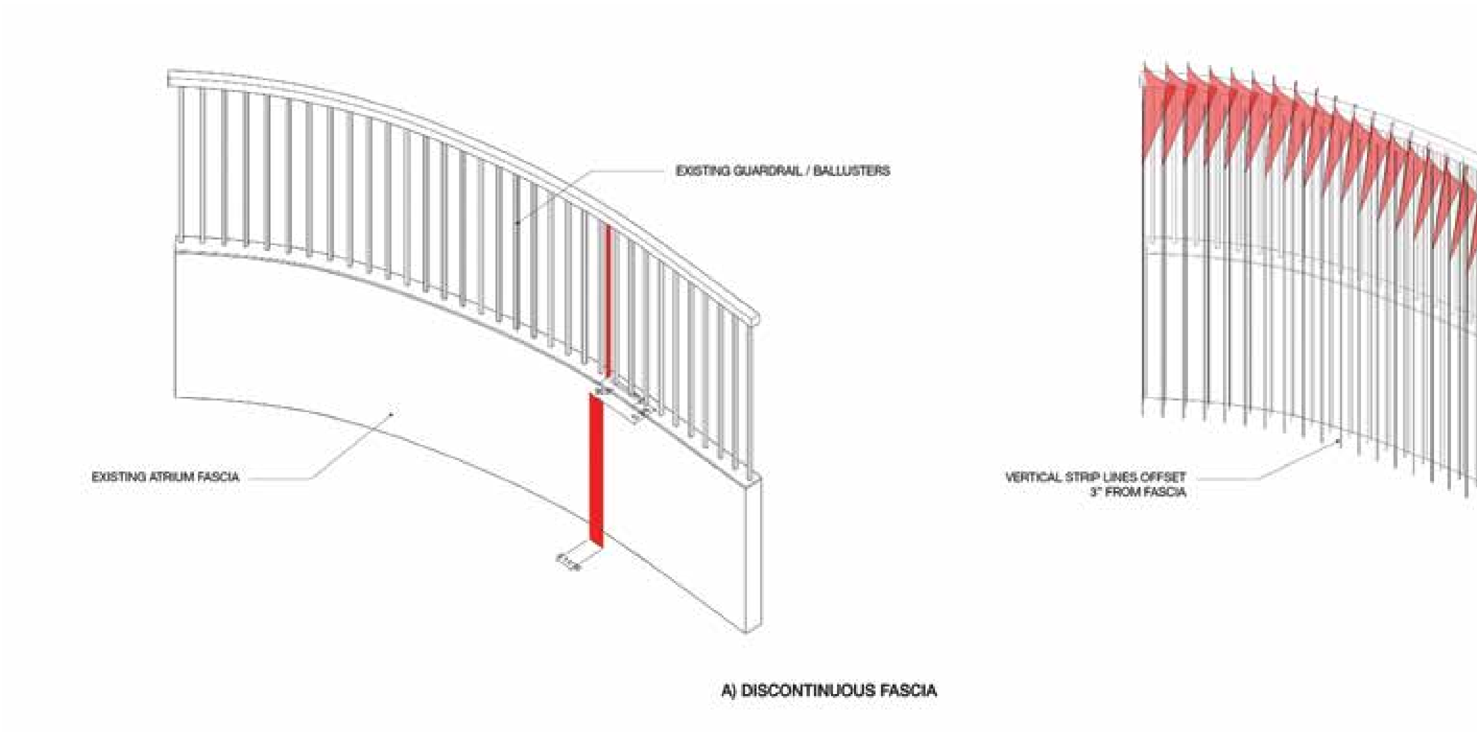
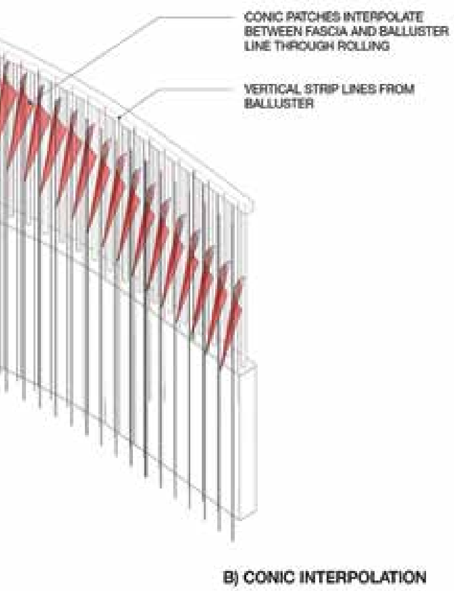
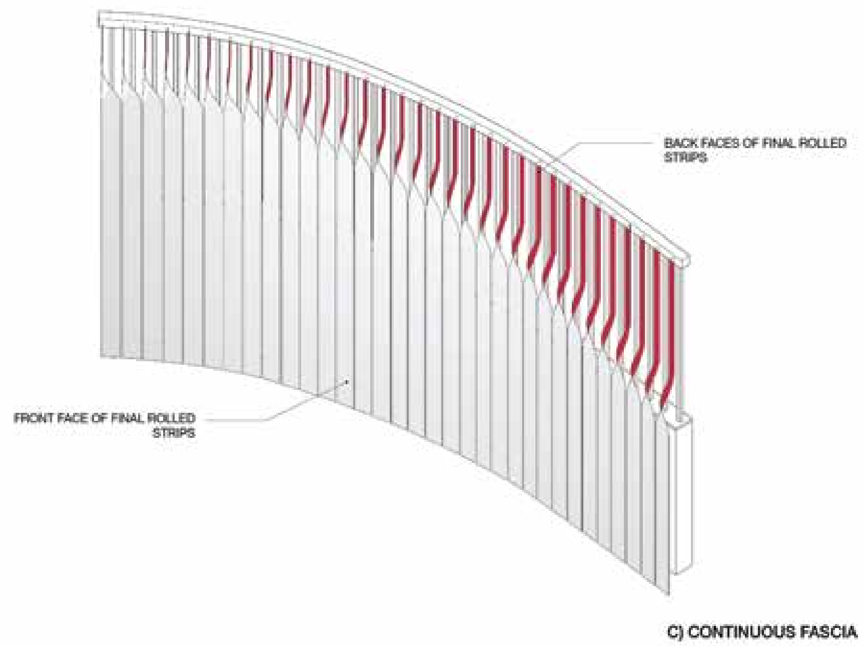


Figure 14: Afterglow: diagram of conic interpolation

(fig. 9) that belongs to the aesthetic subgenre of atmosphere[21] and that my office[22] is currently fabricating and will soon be installing. It is a permanent installation for a new Student Union building at Oregon State University in Corvallis. The building is a four-story structure with a three-story eccentric atrium terminating at the ceiling of the third floor. While the exterior of the building is required to mimic the neoclassicism that pervades the campus, the interior is more contemporary. The atrium of the architecture is comprised of overlapping elliptical figures that stack and contains a public staircase that is integrated with it. We saw this as an opportunity to intersect two diagrams, one planimetric (fig. 10) and one sectional (fig. 11), that fictionalize different formal narratives of the building.

The plan diagram is *empathetic* and understands the architecture of the atrium as an eccentric (in the sense of having multiple centers) space and seeks to amplify that toward the ecstatic by multiplying and extending the radial curves. The sectional diagram is *sympathetic* and understands the atrium as a frustrated dome and rotunda in that the vertical ascension of space is cut short at the last level, never breaking into the sky. Our proposal conceptually forces a dome and rotunda into the existing space, which then undergoes transformation due to the mis-fit. The final result is a two-part intervention (fig. 12). One continuous shredded surface adheres to portions of the stair, fascia, guardrail, ceilings, and walls. A separate ceiling piece





is bounded by an undulating and variable shredded surface with mirrored flat tiles on the interior. The pattern of the mirrored tiles is the flattened projection of two intersecting, hexagonally subdivided hemispheres based on the outer radii of the ceiling figure. The mirror is intended to bring back the vertical effect of the absent dome. But what is relevant to this essay is something more local: the geometry, materiality, and fabrication of the fascia strips (fig. 13).

The atrium fascia is composed of the floor edge and the open guardrail with balusters spaced at 4" intervals. Their current relationship is discrete, in that there is no continuity between them. Our proposal supplements this condition with a continuous shredded surface that mediates baluster, fascia, and ceiling in the form of (or what appear to be) twisted strips. The problematic of the fascia is that there is an almost 6" offset between the strips at the floor's edge and the baluster (fig. 14A). This means that the twisting of a straight, flat strip of material would not resolve the discrepancy without having to add extraneous support. But even then, any sense of continuity would be lost since the guardrail and baluster would remain dis-integrated. The solution employed is a conic patch that interpolates between the outer edges of generic vertical strips with those of the balusters (fig. 14B). This produces phenomenal twisting (fig. 14C) achieved through the rolling of a formed (figured) flat shape. Figure 15 illustrates the geometry and mechanics involved in conic rolling, which is a developable surface since there is no deformation when unrolled. This solution can be situated between the techniques of bending and twisting (fig. 16) in that it is the only one that employs a different operation from the effect it produces.

Similar to the medieval devices for twisting flat stock wrought iron, positive and negative molds were made that allow for the rolling of pre-figured, laser cut strips of aluminum into its final shape (fig. 17). The mold is attached to a pneumatic press the aluminum shapes are slid into until they snap into place. When compressed, the strip is rolled between the positive and negative conic sections. All of the twists are identical, with the one variable being their vertical position along the strip. The result at the individual component is a literal roll/phenomenal twist (fig. 18). As a whole, the atmospheric effect is due to the intensity of color[23] and density of parts. The installation oscillates between being sympathetic with the atrium's multiple centers—by tightly adhering to and smoothing out floor edge, balusters, and ceiling—and indifferent at its edges, where the plan figure folds down at the transparent and opaque partitions (fig. 19).

Indeed, twisted surfaces in architecture are a contemporary phenomenon due in large part to the computer and advanced geometry. But they also have a lineage in related disciplines and other cultural modes of production. At the large scale, the twisting effect seems to have

Figure 15: Afterglow: diagram of conic rolling

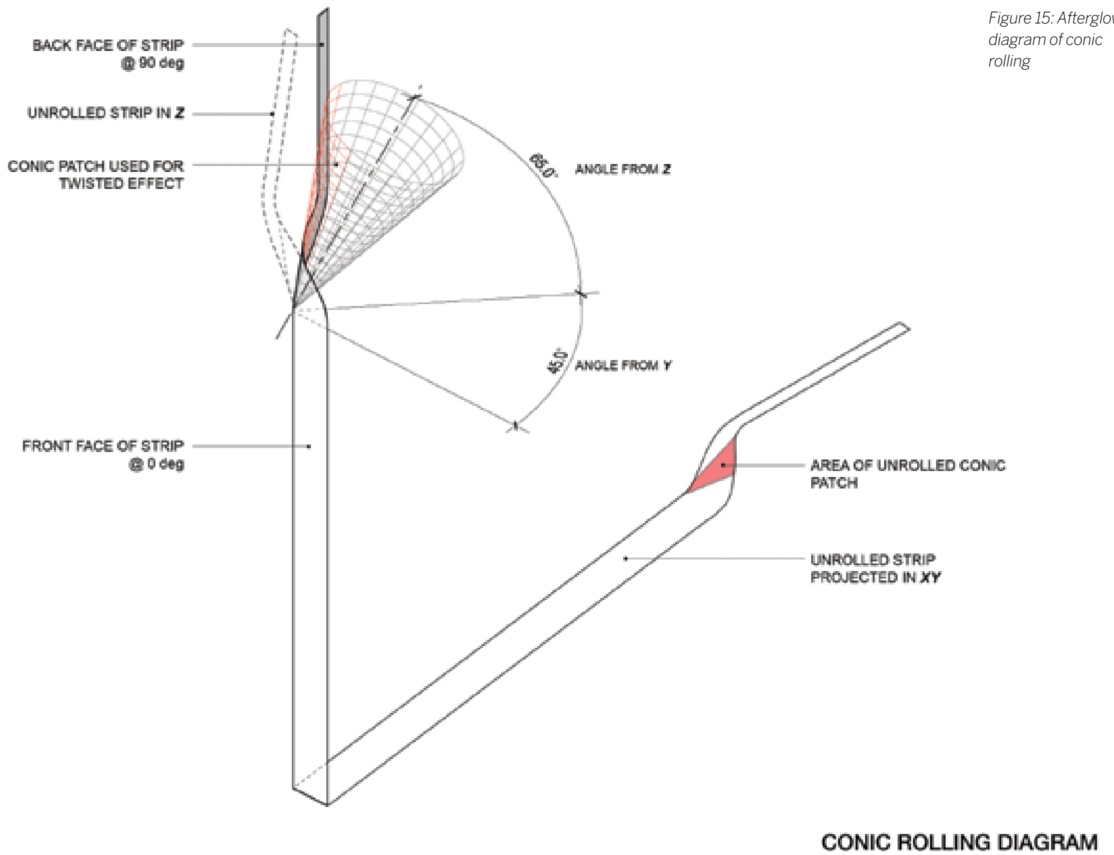
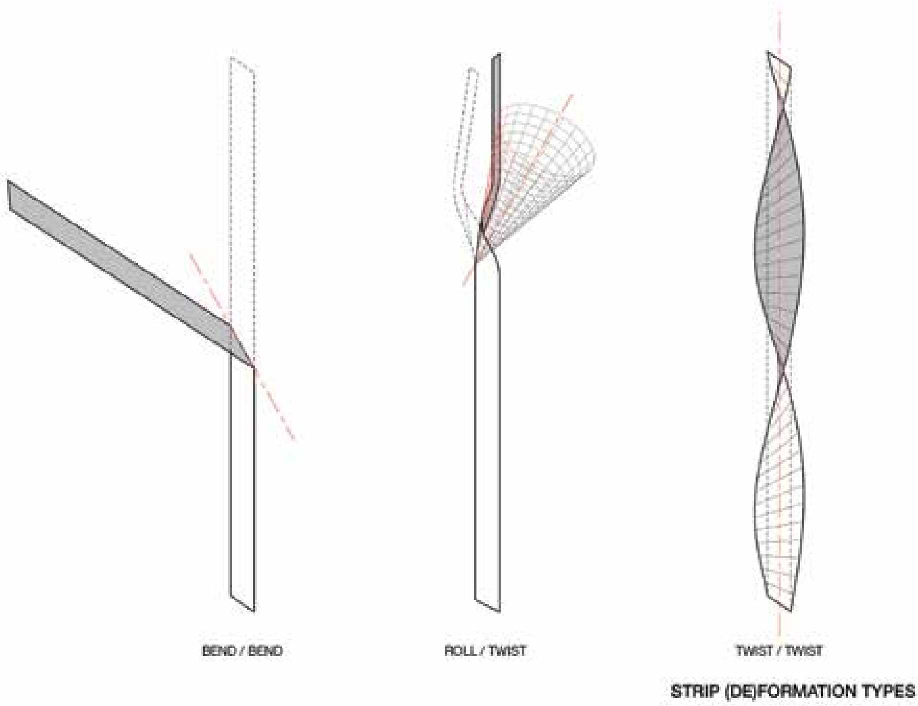


Figure 16: Strip (de) Formation Types



been all but exhausted. It may be that the small scale has also reached its limit in terms of field effects such as atmosphere. The middle scale appears to have the most room left to engender a broader range of effects, such as posture and character. This is due to its ability to address the body and the eye in a sophisticated choreography of space. It can also absorb the effective qualities of the other two scales, producing a possible matrix of twist-on-twist action, both in the literal/phenomenal and geometric/tectonic sense.

The literal/phenomenal template, set up by Colin Rowe nearly 60 years ago, still proves useful across a range of architectural qualities and effects. What is different, and hopefully implicit, in this paper is the attitude toward such a binary framework. The modernist ideal was to sustain distinctions, maintain categorical boundaries, keep the labels in their place. A contemporary attitude allows for the relaxing of initial dichotomies toward strange mixtures, requiring a more complicated form of judgment. Or, as Bruno Latour argues for: "Whatever label we use, we are always attempting to retie the Gordian knot by crisscrossing, as often as we have to, the divide that separates exact knowledge and the exercise of power—let us say nature and culture."[24]

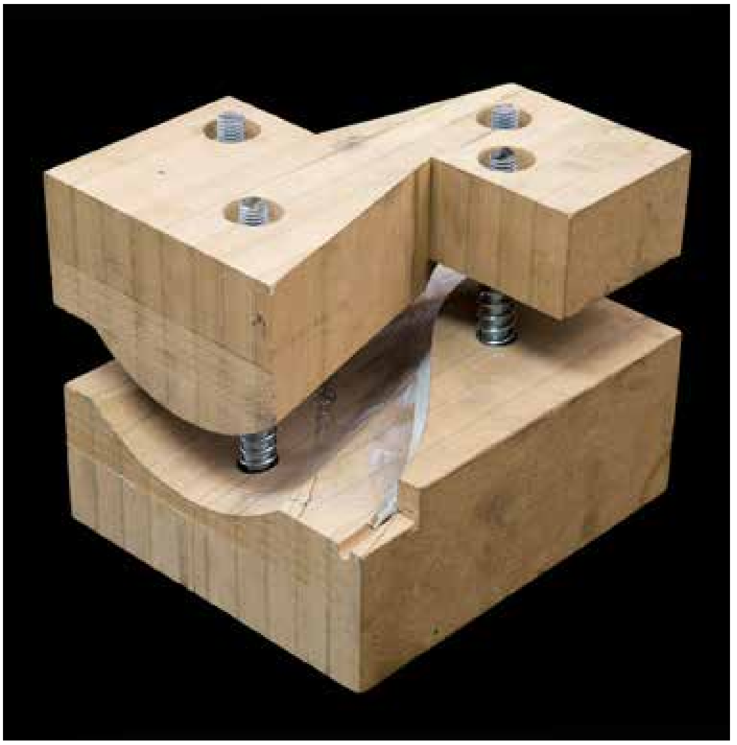


Figure 17: Afterglow: mold for rolling aluminum strips

Figure 18: Afterglow: rolled strip test

ENDNOTES

1. Karel Vollers, *Twist & Build: Creating Non-Orthogonal Architecture*. (Rotterdam: 010 Publishers, 2001).

2. Some examples of this are the Baroque favoring of the ellipse over the Renaissance circle, the Futurists fascination with speed associated with the automobile, and the more recent forays into animate form.

3. This directly refers to Peter Eisenman's notion of "the dislocation of an ever-reconstituting metaphysic of architecture" in the essay "Misreading Peter Eisenman" in *House of Cards* (New York: Oxford University Press, 1987).

4. Christine Keeble, "The Twist and 60's Fad Dances," *How to Jive*. January 31, 2008.

5. Later on I will discuss the geometry of twisting and expand its definition accordingly.

6. In Colin Rowe's essay, whose title this paper is stolen from, he alludes to the notion that literalness is associated with the real while phenomenal merely seems to be.

7. Robert Sokolowski. *Introduction to Phenomenology* (New York: Cambridge University Press), 15.

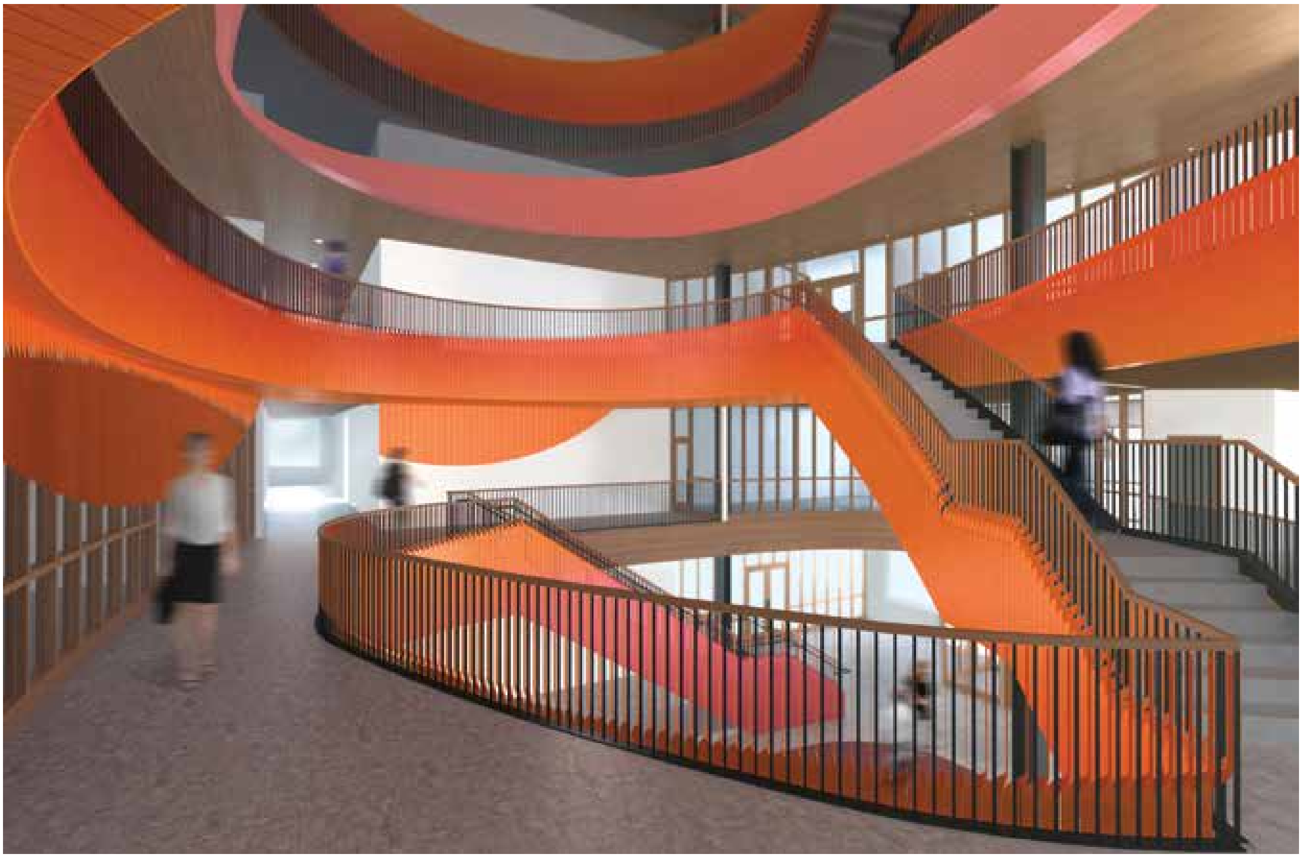


Figure 19: Afterglow: interior rendering

8. Jeffrey Kipnis, "…And Then, Something Magical," in *A Question of Qualities: Essays in Architecture*. (Cambridge, Mass.: MIT Press, 2013).

9. There is a sister Signal Box in Basel that was completed in 1999. They are almost identical except for a massing change whereby the sister version is a trapezoid at ground and a rectangle at the roof, producing a large-scale twisting of one of the facades, as well as ribbon window cutouts of the copper strips.

10. Quoted from Preston Scott Cohen during a lecture given at SCI-Arc in 2009.

11. My gripe with metaphors in general, and with metaphors of the body in particular, is that they are a cheap and easy way to justify or locate value in, for the layperson, architectural forms when they are in fact completely different animals. The twisting of an architectural object at the scale of a tower is a big move and should do more than simply conjure an image of the human body in that same pose. It assumes the layperson's understanding to be too inadequate for more robust associations.

12. You might be thinking that I am about to contradict my earlier, implicit chastising of Calatrava's body metaphor. But this aside has no interest in directly applying these forms to architecture as a stand-in for the body. It is simply a means to understand how the related discipline of sculpture has dealt with the effects of motion through twisting.

13. Andrew Stewart, *One Hundred Greek Sculptors: Their Careers and Extant Works*, Polykleitos of Argos, 16.72.

14. Action in reference to David's battle with Goliath

15. Brigitte Weinsteiger, *The Medieval Roots of Colonial Iron Manufacturing Technology* (Penn State University Center for Medieval Studies), http://www.engr.psu.edu/mtah/articles/roots_colonial_iron_technology.htm.

16. David Hilbert and Stephan Cohn-Vossen, *Geometry and the Imagination*, 2nd ed. (New York: Chelsea, 1952).

17. Wolf P. Barth et al., *Compact Complex Surfaces*, Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge / A Series of Modern Surveys in Mathematics (2004).

18. Stephen Barr, *Experiments in Topology* (New York: Thomas Y. Crowell Company, 1964).

19. Greg Lynn, "Architectural Curvilinearity: The Fold, the Pliant and the Supple," Architectural Design 102 (March/April 1993).

20. Afterglows are the optical phenomena associated with the scattering of light particles during sunset that produces a range of rosy hues in the sky. This effect gets amplified by the occurrence of volcanic ash in the atmosphere, which deepens the color range with reddish hues. While the last major eruption of Mount Hood was over a century ago (1866), it has contributed to the atmospheric effects all across Oregon, and beyond, to this day. This can be experienced during the hour of twilight in certain climatic circumstances (clear to partially cloudy skies) and is one of the elements that makes Oregon's atmosphere unique.

21. I consider atmosphere to be a sub-genre of field effects in architecture, in the perceptual rather than organizational sense.

22. In collaboration with Matthew Au.

23. The aluminum strips are being powder-coated.

24. Bruno Latour, *We Have Never Been Modern* (Cambridge, Mass.: Harvard University Press, 1993).

IMAGE CREDITS

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Figures 1 and 2: Courtesy Herzog & de Meuron

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Figure 4: Left photo via Wikimedia Commons: Jebulon, CC0 1.0: https://commons.wikimedia.org/wiki/File:Replica_Michelangelo%27s_David_black_background.jpg; Right photo via Wikimedia Commons: Black leon, CC BY-SA 4.0: https://commons.wikimedia.org/wiki/File: File: Джованни_Лоренцо_Бернини._ДавИд._01.JPG

Figure 9, 17, and 19: By Amorphis

Rapidly Deployed and Assembled Tensegrity System

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INTRODUCTION

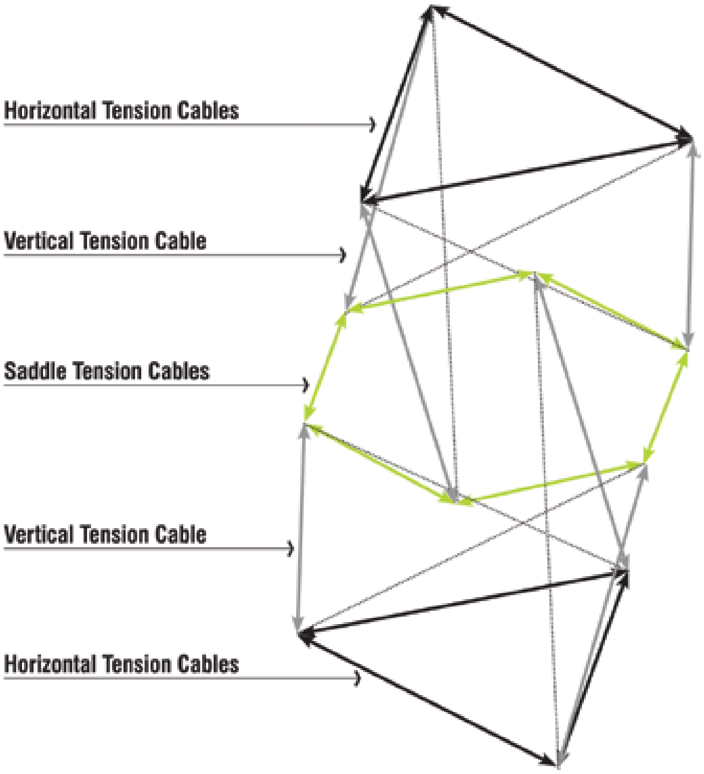
The Rapidly Deployable and Assembled Tensegrity (RDAT) system is developed based on the author) sresearch focusing on the invention of computationally produced performative full-scale building systems and how they can be utilized in an innovative manner in the building and construction industry.[1] Currently, the RDAT research is at the stage of full-scale production of tensegrity masts and plates with variable geometric configurations, including the necessary design, analysis, and production workflow. The goal of the RDAT program is to enable rapid design and deployment of a wide variety of differential-geometry tensegrity structures through computational driven design to installation workflow at the scale of architectural building systems. The project incorporates the integration of parametric and solid-modeling methods to enable computer numerically controlled (CNC) manufacturing of components and the efficient assembly of this complex system in the field through innovative design detailing and production methods.

HISTORIC TENSEGRITY SYSTEM CONSTRUCTION

The RDAT program leverages the advantages of tensegrity structures coupled with advances in science and technology produced since their inception. In 1975, Buckminster Fuller coined the term "tensegrity" as a conjunction of the two words tension and integrity.[2] The term describes a structural system of compressive and tension members that yield mechanical equilibrium. More recently, Pinaud, Masic and Skelton[3] precisely state that tensegrity structures are established when a set of discontinuous compression components interact with a set of continuous tensile components to define a stable volume in space. Recent research in tensegrity has expanded to include those biological systems such as bone and tendon configurations as the study of forces and indeterminate structures through computational analysis has allowed the science in the field to open considerably.

Although contemporary architects and designers now have access to computational tools that could potentially solve the indeterminate structural forces associated with tensegrity structures, very few tensegrity systems are developed within the architecture profession due to some of the inherent features of the structures. The systems tend to be difficult to precisely form, have flexibility under load beyond normative architectural structures, and require

Figure 1: Tensegrity prism structural topology



materials and detailing that are more advanced that is normally possible in building conditions. Renewed interest in deployable structural systems, cable facade systems, and fabric tensile structures demonstrate the need for an interface that architects can use to efficiently develop tensegrity designs prior to completing the cumbersome calculations traditionally associated with indeterminate form-finding.[4] For example, Kenneth Snelson's tensegrity sculptures are the embodiment of the Fuller and Pinaud (et al.) definitions of tensegrity. His methodology is based upon physical model building, numerous measurements, and iterative refinement of tension cable lengths on the final unique piece. Research completed at the Max Planck Institute for Intelligent Systems in Stuttgart states that one analytical form-finding method exists that requires the designer to predefine the cable length but then calculates the ratio directly without involving the iterative process.[5] Contemporary computational tools can be hardest to bring about a more efficient integration of digital and physical production in the creation of indeterminate structures.

Tensegrity structures offer numerous advantageous properties. As three-dimensional self-stressing cable systems, they have a relatively small number of disjoint compression members (fig. 1). They are self-erecting, in that tensioning the final cable transforms them from a compact group of members into a large three-dimensional volume.[6] As such, tensegrity systems are extremely lightweight and materially efficient, embody resilient properties, allow system flexibility, and are composed of primarily standardized linear elements. In addition, within the RDAT system, they are now calculable, easy to assemble, and reconfigurable, offering po-

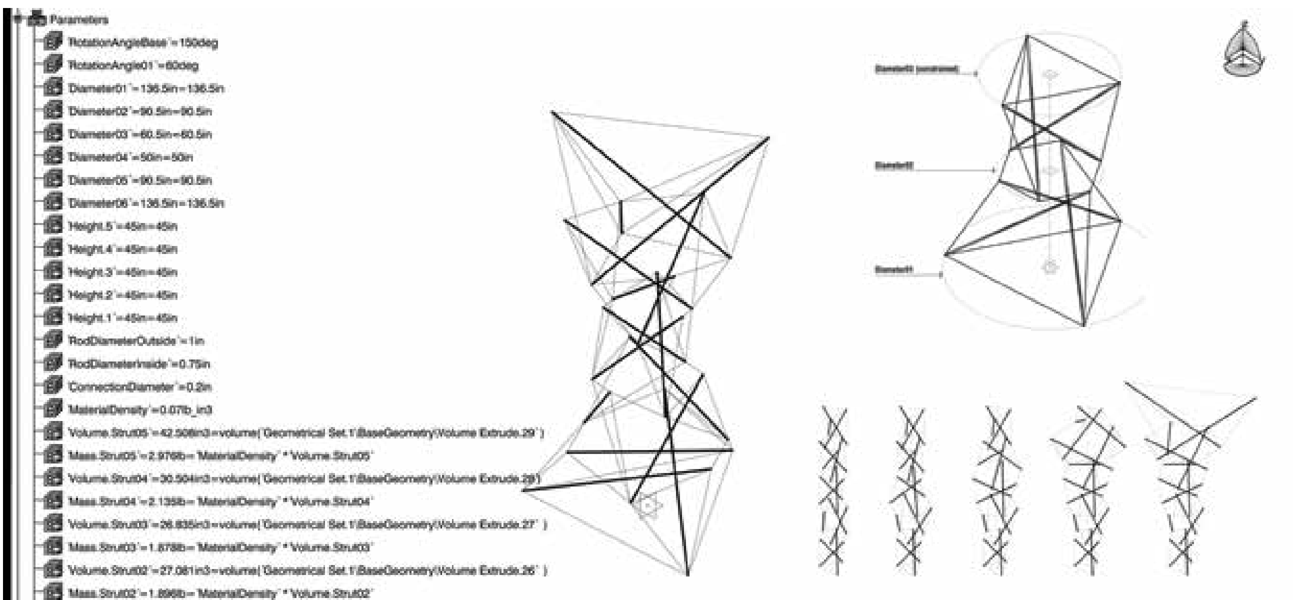


Figure 2: RDAT interface for adjustment of prisms

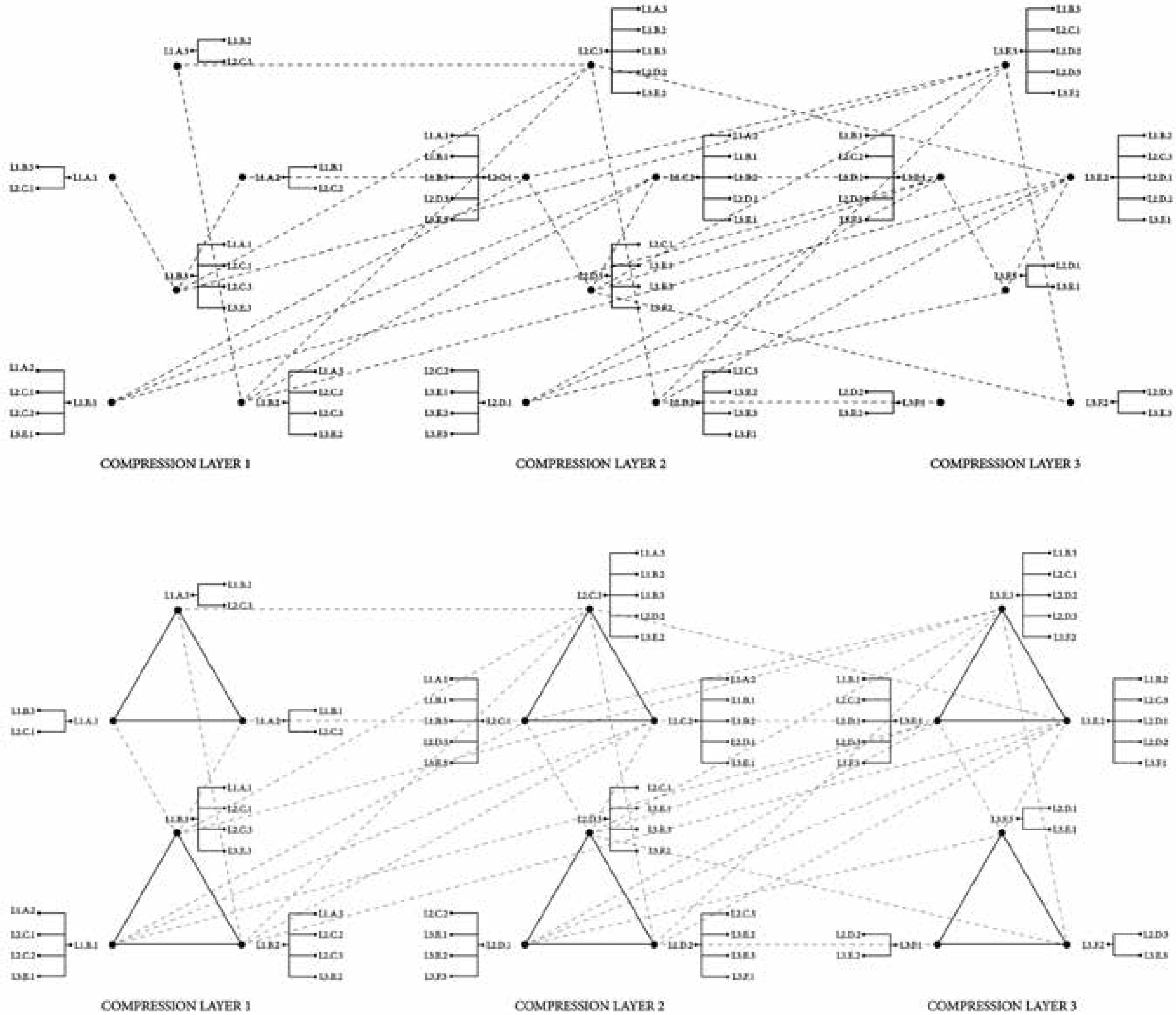


Figure 3: RDAT tools allows for free design while retaining fabrication specifications

tential uses as structural reinforcement, infrastructural elements, reusable or left-in-place formwork, scaffolding, and other building construction elements, as well as the well understood use as flexible building components such as roofs, curtain-walls, and other similar systems.

RDAT DESIGN METHOD

As a design methodology, the RDAT system integrates these properties with digital design tools, a detailed set of components, and digital fabrication technologies into a cohesive system, mitigating the interoperability issues associated with existing cross-platform design, analysis, fabrication, and project delivery methods. The goal is to develop an optimized, project-dependent workflow to resolve interoperability conflicts by adapting existing solutions and proposing innovative alternatives.

Since the late 1980s, architects and engineers have used computer-aided design and manufacturing (CAD/CAM) tools to develop building projects while narrowing the gap between representation and fabrication. Researchers have argued that advances in digital design and fabrication have led to a triumph of appearance over substance and that few truly new materials, features, and processes have resulted from the proliferation of digital design techniques. Furthermore, the reliance of architects on craftsmen and fabricators to carry out their designs suggests that architects are disconnected from the skill of making. Research on the use of digital design tools (CAD/CAM, BIM, scripting and computational analysis), project delivery methods, and fabrication technologies, in order to synthesize full-scale case study projects led to new proposals to develop the use of

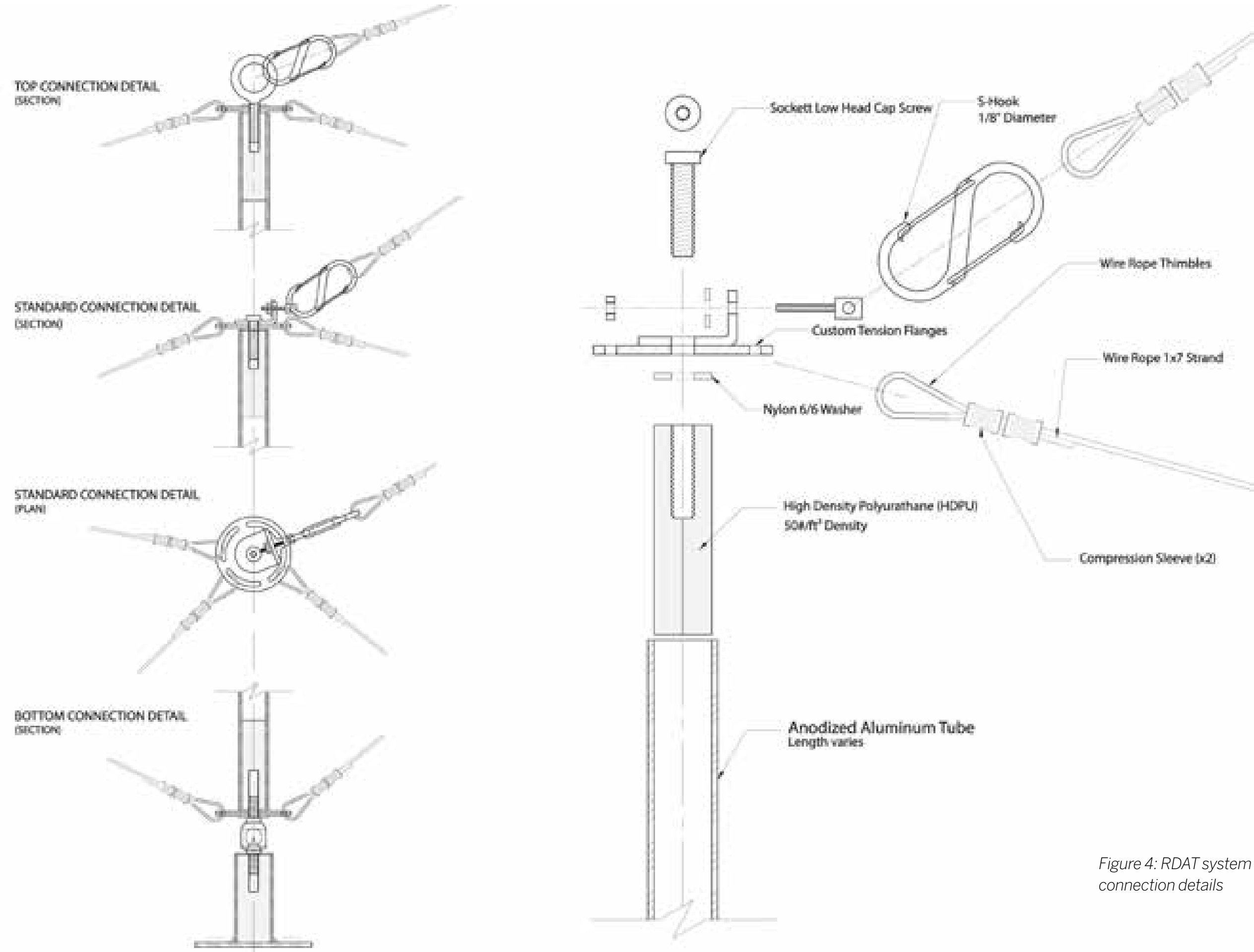


Figure 4: RDAT system connection details

innovative materials and novel processes, and ultimately, to reintroduce making to architects as an integral component of digital design and fabrication.[7]

Prototyping done within the framework of existing software is a critical method of rapidly developing a set of processes for testing, while simultaneously developing the criteria for the eventual programming of the custom design and analysis tools that the author is currently engaged in. Using CATIA Generative Shape Design and CATIA Knowledge Patterns combined with Rhino and Grasshopper studies, the RDAT system concludes with the fabrication of a tensegrity tower derived from designs parameterized in the computational system through a customized program interface (fig. 2). The digital and associated physical fabricated components address pre-stressing or post-stretching of the tension elements during the assembly process, as well as assembly tolerances, while being able to track each category of element for optimizing strength, assembly sequence, and inventory (fig. 3).

The RDAT detailing was developed to allow for variable parametric assembly processing with the ability to be quickly deployed, demounted, and reassembled for numerous tension line configurations. Additionally, the node is simple to construct, as strong as traditional tensegrity connection methods, efficient, and elegant (fig. 4). The fundamental process relies on the inherent compressive forces on the strut at the node detail by the combination of three acute angle tension wires and one obtuse angle wire. At each node, the three-dimensional vectors combine to a resultant vector that is always directed into the node, thus preventing the separation of node and strut (fig. 5). This allows for rotation to relieve internal stresses from system flexing, and the struts easily engage and disengage during assembly and demounting of the structure.

The RDAT node, currently under patent application, is fundamentally composed of a cylinder of material that is machined to fit within the strut. In the case study, fabricated high-density polyurethane foam was used to

Figure 5: RDAT node in Urban Forest case study

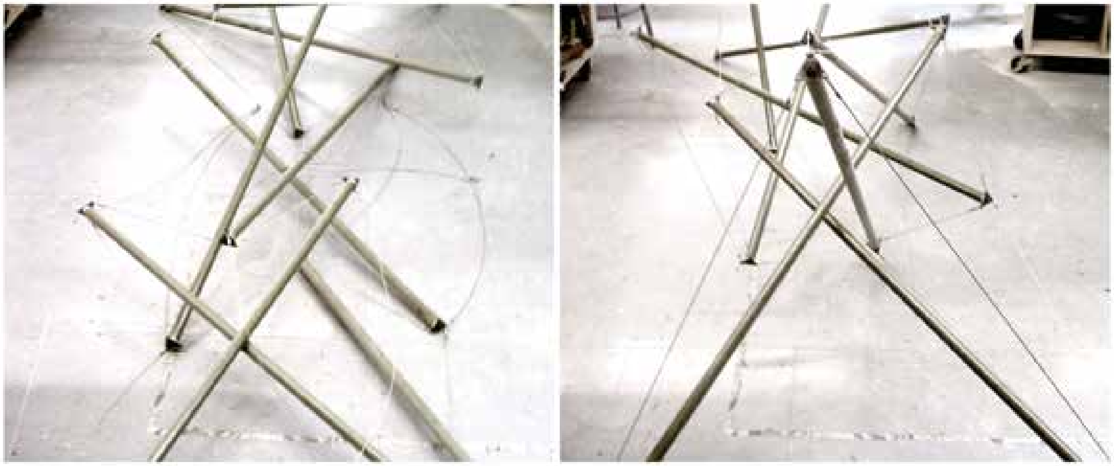


Figure 6: Final assembly step in RDAT tower

Figure 7: RDAT six-meter tower is light enough to be erected by only one or two people

prototype the cylinders to fit snugly within the anodized aluminum tubes. The CNC equipment was used to tap a thread into the center of the cylinder for the attachment of the connection disk. The connection disk is a disk of plasma-cut steel that can be bolted to the cylinder as well as connected to the four tension lines at the node. The cutting of the disk is detailed to allow for tolerance at the tension connections; the load is transferred to the disk and strut simultaneously for seamless force-flow through the system.

Once all elements are produced using extracted computer model data, the process for assembling a completed tensegrity prism is 1) construction of nodes, 2) assembly of an end-prism, and 3) attachment of the remaining prism elements linearly to the end-prism (fig. 6). Once constructed on a horizontal surface, the structure is lightweight enough to be positioned vertically by one or two people, depending on the height of the complete structure (fig. 7). If the structure is to be demounted and transported, the procedure is reversed:

place the assembly in a horizontal position and 1) remove the primary tensioning cable at one end-prism, 2) collapse the end-prism, 3) remove one cable from the adjacent prism, collapsing the prism, repeating step three until all prisms are collapsed, and then bind and fold each set of rods on the others until a single package of rods and cables is collected and bound together (fig. 8). While assembly is longer in duration than disassembly, a five-prism structure such as the case study has been assembled in as little as one hour.

Figure 8: RDAT six-meter tower packed for shipping

RDAT COMPUTATIONAL/ PRODUCTION HYBRID METHOD

Production of a tensegrity structure—fabrication, assembly, and installation—has historically been the site of trial-and-error methods as described above. The RDAT system integrates the design, analysis, fabrication, and assembly of the system through developments based on the authorsseprevious work in advanced networked structural systems. A critical aspect of the development of a seamless workflow is the step between the computational form-finding and analysis and the manufacturing of the components for physical construction. The creation of a detail that is designed from its inception to conform to the algorithms and parameters that are incorporated into the software, including geometry, material properties, degrees of freedom, and other aspects of the system, is essential to assure that the produced components have the capacity to perform as designed. Simultaneously, a feedback loop is put in place to allow developments during prototyping, case studies, and physical testing to integrate results into the programming of the CAD/CAE system to ensure that the computational component conforms to the production component. Through a series of case studies where building scale production is realized, the system can be tested against performative and production criteria.

CASE STUDY 1: URBAN FOREST, MONTPELLIER, FRANCE, 2010

The *Urban Forest* installation was assembled at the Seventh Annual Festival des Architectures Vives exhibition in Montpellier France in June, 2012, and served as a test for rapid deployment of a full scale system due to the requirements of erection within one night. The structures are composed of three six-meter tall conical tensegrity towers of anodized aluminum compression members and stainless steel tension members (fig. 9). Installed in the Hotel de Griffy courtyard in Montpellier, the towers suspend a network of metallic mylar "leaf" elements that reflect and colorize sunlight through dichroic action as it streams down the courtyard to the inhabited space below (fig. 10). The modified five-prism tower structure incorporates an innovative nodal design allowing for rapid deployment with a minimal amount of time and labor, and folds to fit a shipping container measuring two meters long and 50 centimeters in diameter.

Figure 9: Urban Forest installation in Montpellier, France

Urban Forest is a prototype for digitally fabricated tensegrity structures in the form of self-supporting towers, and a means to demonstrate and test the structural strength as well as its formal capacities. *Urban Forest* is an initial prototype driven by ideas in the greater context of potential architectural applications, such as efficiency in materials, structural strength, and other technical

Figure 10: Urban Forest installation in Montpellier, France

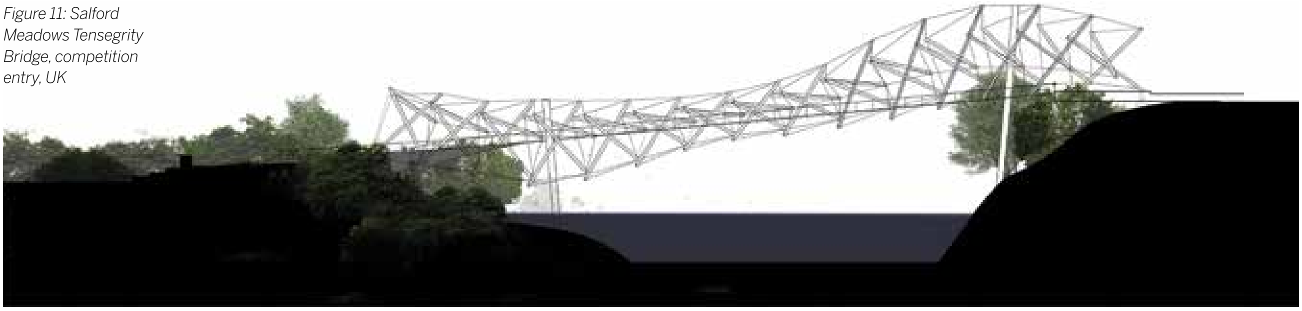


Figure 11: Salford Meadows Tensegrity Bridge, competition entry, UK

Figure 12: Salford Meadows Tensegrity Bridge, competition entry, UK

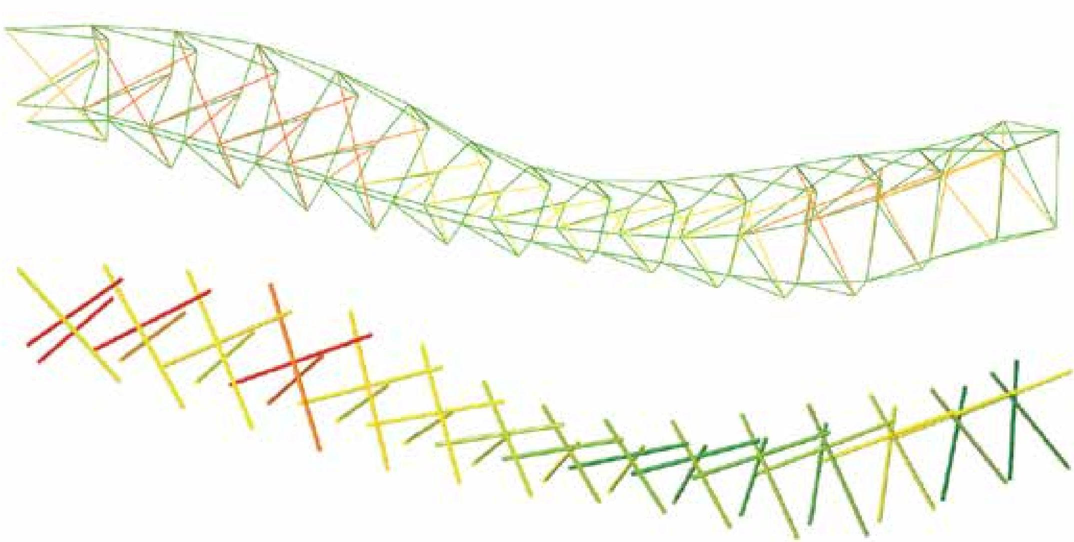


Figure 13: Tensegrity tensions and compression structural analysis

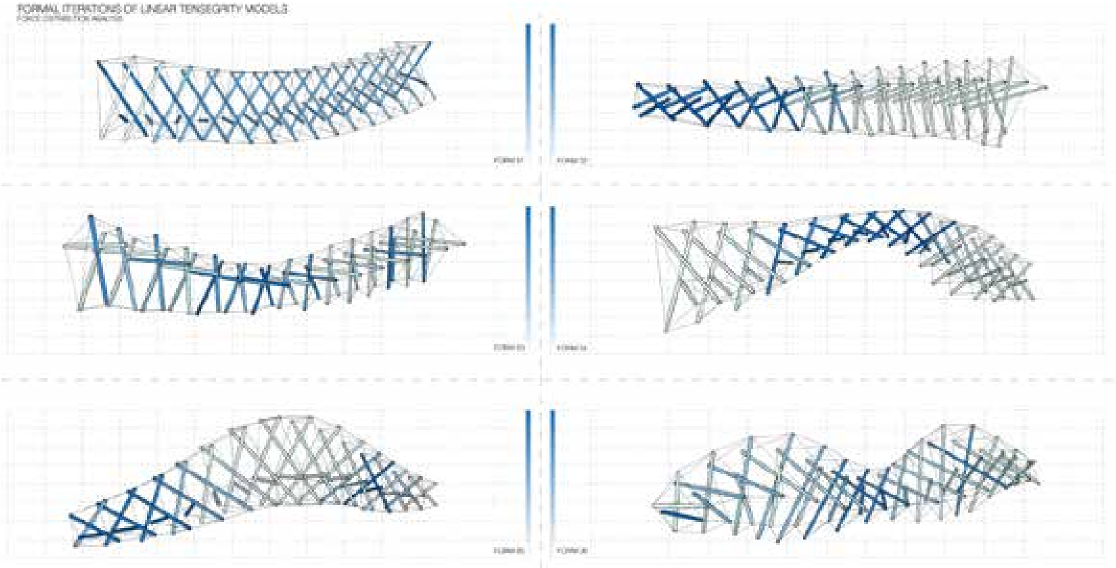


Figure 14: Form-finding algorithm iterations

Figure 15: Rendering, Toward a New Industry installation, AIA Center for Architecture, NY

benefits. Tensegrity presents a system that is easily transportable, collapsible, and has the potential to create large walls, enclosures, and structures with a minimal amount of materials.

The *Urban Forest* case study was used to test the ability to prefabricate the components in place within the structural configuration, collapse the structure for shipping, and redeploy with a minimal of time and labor required. This project was erected in France by one person over the course of an evening, proving that the design concept was sound while revealing potentials for improvement in the design and detailing that were added to later iterations.

CASE STUDY 2: SALFORD MEADOWS TENSEGRITY BRIDGE COMPETITION, 2013

The Tensegrity Bridge entry for the Salford Meadows Bridge Competition seeks to provide a needed link between Salford Meadows and the surrounding community, while simultaneously promoting an efficient and functional structure and celebrating the future potentials of Manchester (fig. 11). With a nod to the rich industrial past of the local community, the innovative tensegrity structure proposed reinforces the dynamic nature of the nearby Engineering Faculty of the University of Salford and develops a catalyst for encouraging future growth (fig. 12). The importance of the local community demands a world-class structure as a response to the development of the city.

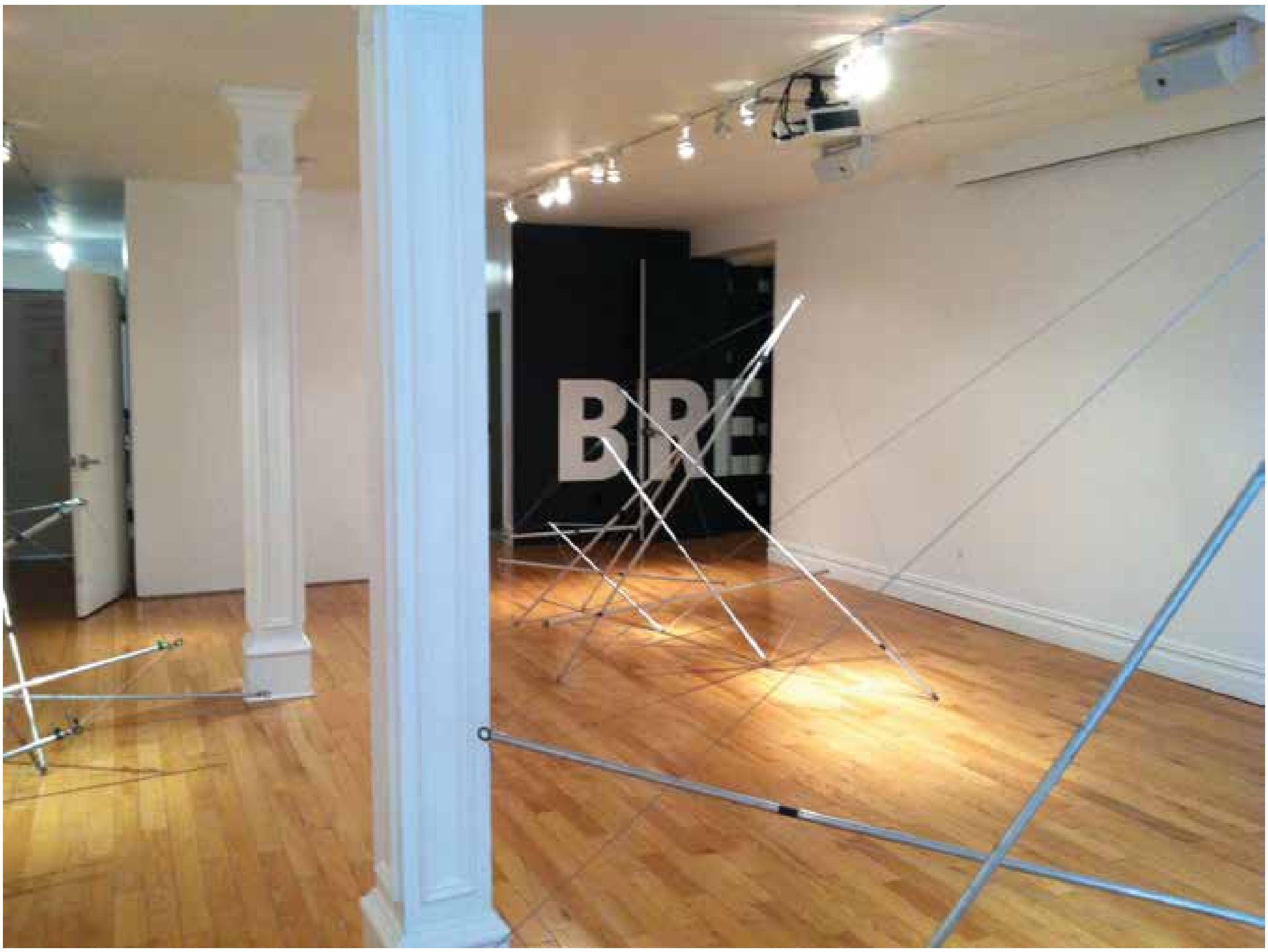
Tensegrity Bridge was developed through an in-house computational program to streamline the design, analysis, and production of a tensegrity system through parametric solid-modeling and computational physics simulations, allowing for the formulation of a sinuous shape that weaves the cable supports around a linear direct pathway (fig. 13). The design strategy develops the potential of Salford Meadows by creating a link and attracting new visitors, while expressing the bridge as a landmark through the highly visible configurations at the landings of the bridge. The system is engineered to take advantage of the forces developed in a pedestrian bridge of this scale through computational sizing and configuration of the elements and the tensegrity form. The structure is naturally resilient and self-tunes to develop counter-vibration, dampening movement due to passage of pedestrians. Suspension supports for the footbridge, connected with an isolating detail, reduce vibrations through dispersing the forces in the naturally resilient tensegrity system. The lightness of the structure reduces the need for extensive foundations at the embankment so that support can be focused primarily on two point loads above the river, providing a less invasive grounding condition and simultaneously expressing the gracefulness of the proposal.

This competing entry allowed for the study of a full-scale application with the collaboration of Dr. Will Laufs, an engineer with extensive specialty structures expertise, including tensegrity structures. The author was able to test the form-finding and analysis of his computational format in response to the program and the engineerlysadvice (fig. 14). Further refinements in the algorithms used resulted from the application of the system at bridge scale.

CASE STUDY 3: AIA CENTER FOR ARCHITECTURE INSTALLATION, NEW YORK, NEW YORK, 2014

The *Towards a New Industry* installation quietly explores the ambient possibilities of new industry, tensegrity systems, and new media with an exhibition of projects and content related to AECOM's 2014 student competition Urban SOS: Towards a New Industry. Featuring video integrated in three tensegrity sculptures, the exhibition curates the four finalist projects as well as schemes from other program participants. The system is a triad of self-supporting tensegrity towers where the placement of the structures allow individuals to freely circulate around each respective tower, experiencing the layering of materials and video projection from different vantage points (fig. 15). The self-supporting nature of the tenseg-

Figure 16: Toward a New Industry installation, AIA Center for Architecture, NY



rity towers introduced a unique design and fabrication challenge. The formal quality of the sculptures along with an intelligent use of materials required the collaboration and expertise of various designers (rounding condition and simultaneouone which defines the success and spirit of the Urban SOS program.

The *Towards a New Industry* installation allowed the author to further refine the system to include adjustable detailing for field modifications (fig. 16). The addition of relatively high weight projectors to the system on-site posed a challenge to the form-finding algorithms that needed to have adjustment capabilities once installed (fig. 17). A novel adjustable node and strut system was added that accommodated changes on-site to the system and loading conditions, bringing the RDAT system closer to the goal of an automatically actuated system.

CURRENT RESEARCH AND FUTURE DIRECTIONS

Initial research partially addresses digital design and fabrication issues with tensegrity systems, but more importantly, it exposes the disconnect between ease of digital design and the realities of constructing complex geometric systems. In particular, the tensegrity tool provides the designer with a CATIA dependent workflow that adjusts the tensegrity structural system based upon user inputs while also generating the necessary fabrication specifications. However, successful deployment of a tensegrity structure remains in the execution of the assembly methods used outside of the digital design and digital fabrication toolbox. Furthermore, synthetic biology research affirms the need for physical testing of prototype composite materials in order to validate the computational analysis. With the existence of an optimized digital workflow, efforts should be focused on developing an interface for transitioning digital design content into manufacturable objects by adapting existing fabrication technologies or designing new fabrication solutions.

The goal of future work will be to contribute to the design, production, and realization of innovative projects through continued research in digital design and fabrication technologies (fig. 18). Current developments include generalizing the prism geometry beyond three struts, expanding the mast structure into a planar surface, and incorporating actuated sensing and programmed systems into the structure. Currently, work is being initiated by the author at the CUNY College of Technology in collaboration with interdisciplinary teams to innovate in the computational algorithms and interface (with the Computer Engineering Technology Department), and to develop a reconfigurable MEMS joint and strut system that will allow tuning and topology adaption (with the Mechanical Engineering & Industrial Design Department) and a system to research modes of automated assembly in on-site constructor conditions (with the Civil Engineering & Construction Management Department). Future interdisciplinary research trajectories include the incorporation of energy generating and storage strategies with a robotics industry partner as part of a building integrated system.

Figure 17: Toward a New Industry installation, AIA Center for Architecture, NY

ENDNOTES

1. For instance, see the author's "Systems and Methods for Construction of Space-truss Structures," USPTO# US20060254200.

2. R. B. Fuller, *Synergetics: Explorations in the Geometry of Thinking* (London: Collier-Macmillan,1975).

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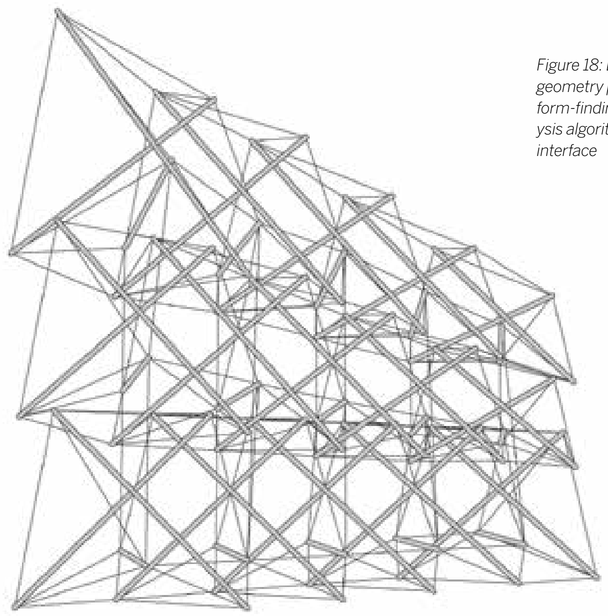
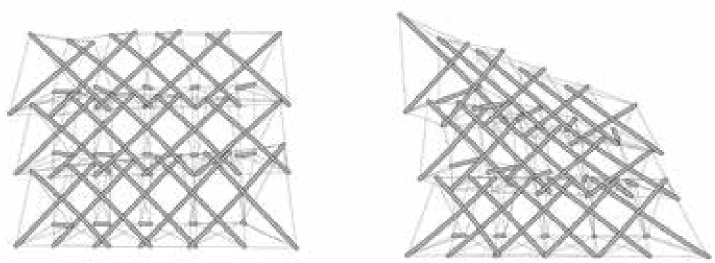


Figure 18: Differential geometry planar form-finding/analysis algorithm and interface



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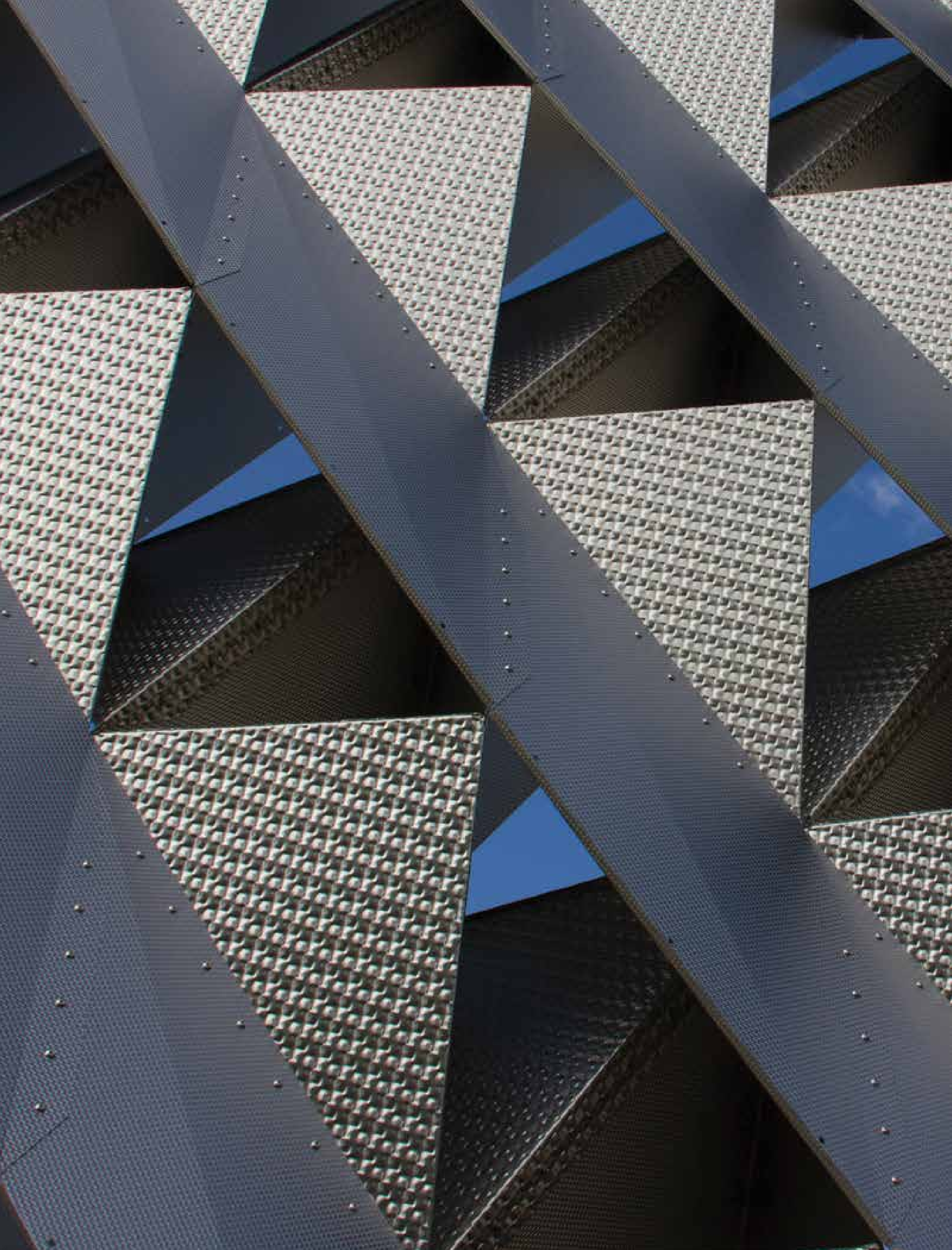

Collaborative Models between Academia and Industry: Experiments and Applicability

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INTRODUCTION

This paper will present strategies for forging collaborative architectural practices between universities and manufacturing industries. It will focus on current architectural research, its explicit impact on manufacturing processes, and the influence of these processes on design outputs. Specifically, the authors will discuss examples of collaboration between faculty and students at the University at Buffalo Department of Architecture, and, initially, manufacturing industries based in the Buffalo area, but more recently, a network of architects, manufacturers, and engineers spread across the globe. These include: 1) the initiation of a working relationship between the Department of Architecture and a local textured metals manufacturing company, Rigidized Metals Corporation (RMC), through the development of a student design competition and graduate design seminars; 2) the development of further research by faculty and students on the structural capacities of folding stainless steel, and the development of an experimental prototype, *project 2XmT*, that demonstrates the aesthetic potential of this research; 3) *project 3xLP*, the winning submission to the international TEX-FAB SKIN competition that coupled the authors and RMC with material and fabrication support from A. Zahner Company and engineering support from ARUP, thereby rapidly expanding the reach and momentum of an emerging research practice; and (4) forging new collaborations with manufacturing companies spread more broadly across the globe, specifically the Absolute Joint System (AJ) based in London, England, allowing our team to integrate a wider range of materials and digital technologies into our workflow, while moving our research toward a marketable product.

Using the framework outlined above, this paper has four thematic objectives: to describe the procedures by which two faculty developed, designed, and fabricated a prototype in collaboration with an industrial manufacturer, and utilized the described framework in developing a proposal for an intense collaboration; to identify how architects are utilizing digital tools to facilitate collaboration among diverse architecture, engineering, and construction (AEC) teams with the goal of merging design and construction into an integrated workflow; to catalog how new means of interfacing with information and an increased proximity to the production of products/objects through CNC machinery is radically reshaping a renewed material-centric practice in architecture and its related fields; and to assess the capacity of parametric design software and how this method of working/thinking has allowed architects to streamline drawing-to-production methods.

MODEL 1: FACULTY AS ORGANIZER

The first collaborative model begins on campus under a loose pedagogical theme to explore architectural applications for RMC, a local textured metals manufacturer based in Buffalo, NY. The company is unique for its cold-rolling process of embedding geometric textures into thin gauge metals (fig. 1). The approach was strategically split between two graduate seminars, one, led by Nicholas Bruscia, which focused primarily on specular effect through subtle geometric variation (patterns and folds), and the other, led by Christopher Romano, which focused on self-structuring thin-gauge metal surfaces using similar methods. It was an extremely exploratory phase, with students testing a number of preliminary issues that were based on individual interests: unrolling geometric surfaces, folding metal, and mapping a range of specular qualities inherent in the metal. This semester-long process included a tour of the manufacturing facility, an introduction to the material and manufacturing process by Rick Smith, president of the company, and week-to-week feedback provided by the course instructors. This structure resulted in a series of student groups working collaboratively on small physical prototypes and using the tools and technology available to them within the university to simulate the effects of rigidized metal and the fabrication workflow of the manufacturer (fig. 2). As the large majority of the research was being conducted within the university, there were no monetary or logistical risks assumed by the manufacturer. At the conclusion of the semester, students presented their work to the president of the company and a small group of administrative staff at RMC.

To begin to unpack the benefits of this type of interaction, the manufacturer had a large group of students, who were near graduation and about to enter the workforce, touring its facilities and learning about its product, which alone is an enormous benefit to any manufacturer. In addition, students free from any economic or logistic constraints were able to ask questions, design freely, and introduce contemporary parametric software to the manufacturer, which we felt could be of potential use to the manufacturer in the future. As a model that is implemented in the initial phases of a manufacturing relationship, it is useful for the structure to be more traditional so as to allow the academy to engage with imaginative *thought experiments* based on *real-world material contingencies.* The advantages for both parties emerge naturally as the relationship moves away from students and faculty simply applying new information toward the completion of a single self-guided project, to the production of new knowledge whose ultimate goal is real-world applicability.

MODEL 2: FACULTY AS MATERIAL SCIENTIST

The second collaborative model proposes a faculty-directed research structure that allows the Department of Architecture and local and regional manufacturing to collaborate on the development and full-scale testing of architectural applications for their product line. This includes finding new potential in existing products, and the development of new techniques and optimization of existing processes through the use of digital tools for both design and fabrication. The research collaboration detailed below is used to explain how this model builds on prior collaborative work completed within two graduate technical methods seminars described in Model 1, while synthesizing these pedagogical approaches into a singular research proposal.

In this model, much of the effort is two-fold: material testing a manufacturer's existing product line, and attempting to extract the unwritten knowledge that collectively exists amongst the fabrication team. A challenging and crucial next step is attempting to document this data in some kind of quantifiable and measurable format that can be used to inform future design decisions. To that end, we conducted extensive testing: photographic documentation of the exterior light reflecting and diffus-

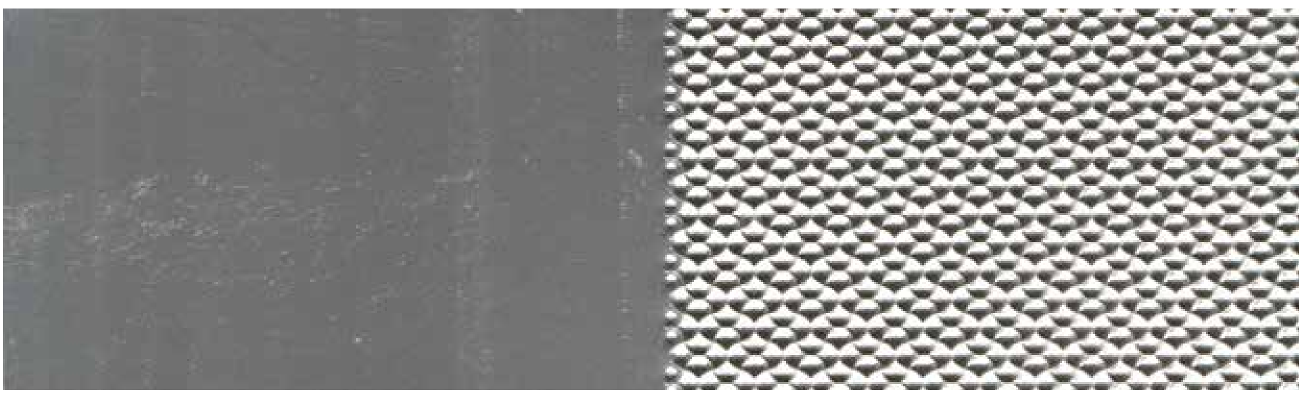


Figure 1: Comparison of 22GA (.029") plain stainless steel vs. rigidized metal 3ND texture

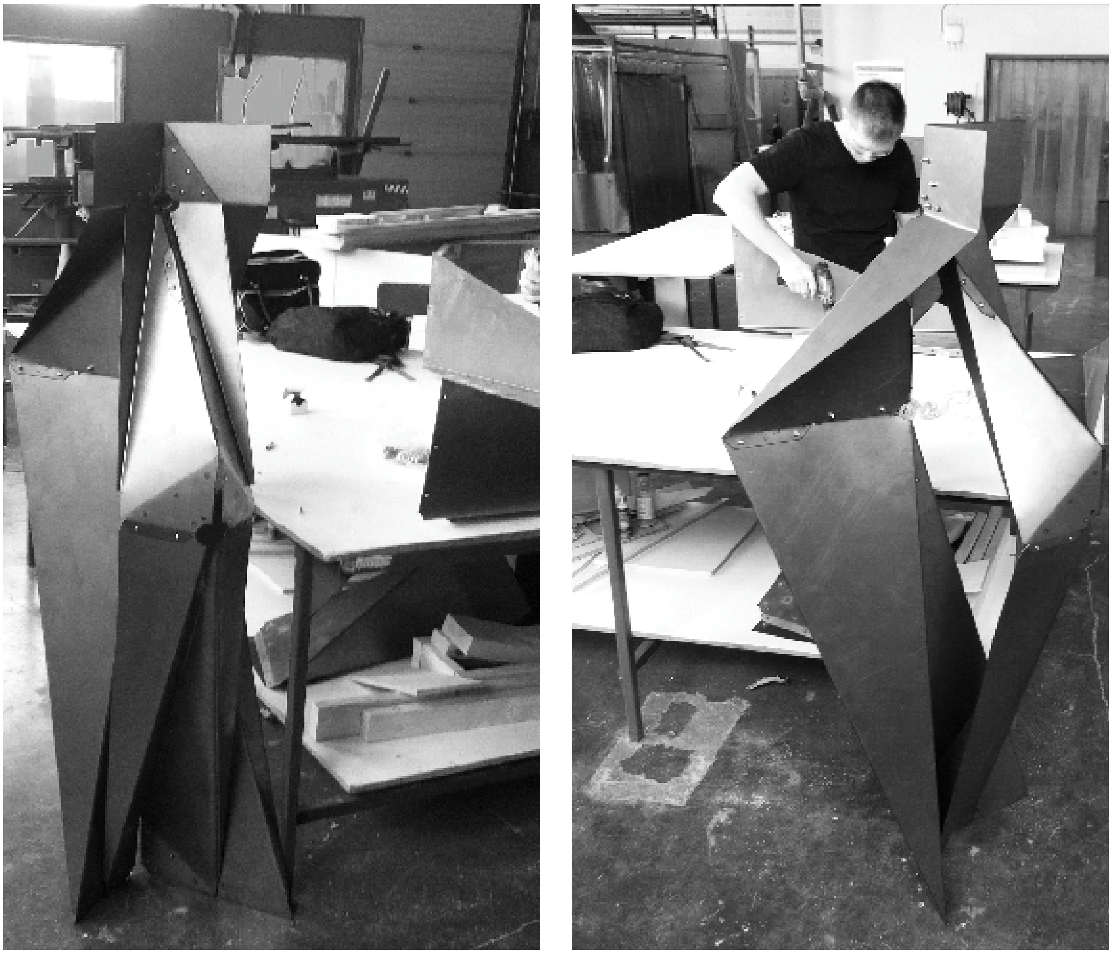


Figure 2: Graduate Technical Methods Seminars – full-scale prototyping of self-structuring metal surfaces using 22GA carbon steel

ing qualities of textured metal under a range of weather conditions; strength comparisons of plain stainless vs. textured stainless; 3-point deflection testing of some of the more common patterns to pinpoint which patterns yielded the highest structural performance; and extensive metal folding studies to reveal to the academic team the fabrication limits of both the hydraulic turret punch and hydraulic press brake. This process yielded a decision-making process that was based on empirical data instead of relying on rule of thumb or repeated cycles of trial and error.

To understand how we framed the research, it is important to have a more detailed understanding of *rigidizing* as a manufacturing process—rolling geometric textures into ordinary sheet-metals to increase the cross-sectional depth of thin-gauges by distributing metal above and below the neutral axis, resulting in a much stiffer material that provides thinner and lighter gauges with increased structural capacity. At the same time, the process gives the material dynamic light diffusing qualities. To summarize, both specular quality and surface rigidity result from the same geometric conditioning of the metal, and we felt these material characteristics had not previously been studied or exploited. While a more typical use of the this material is for non-structural facade elements or interior panels backed by substrates, the intention of this research is to develop a self-supporting architectural system that reveals the existing but underutilized structural potential of the material while simultaneously exhibiting the specular quality of the texture. Our research culminated in an experimental prototype, *project 2XmT*, which uses a framework of arrayed octahedrons and thin-gauge textured metal to generate a self-structuring skin that

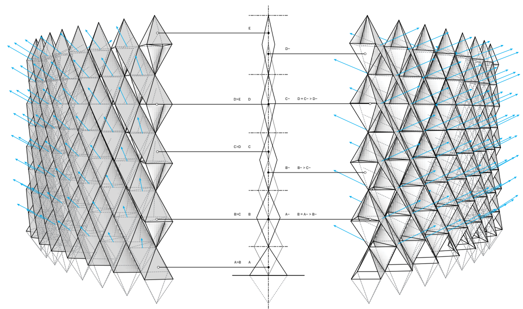


Figure 3: project 2XmT – rendering showing framework of arrayed octahedrons with thin-gauge metal panelization

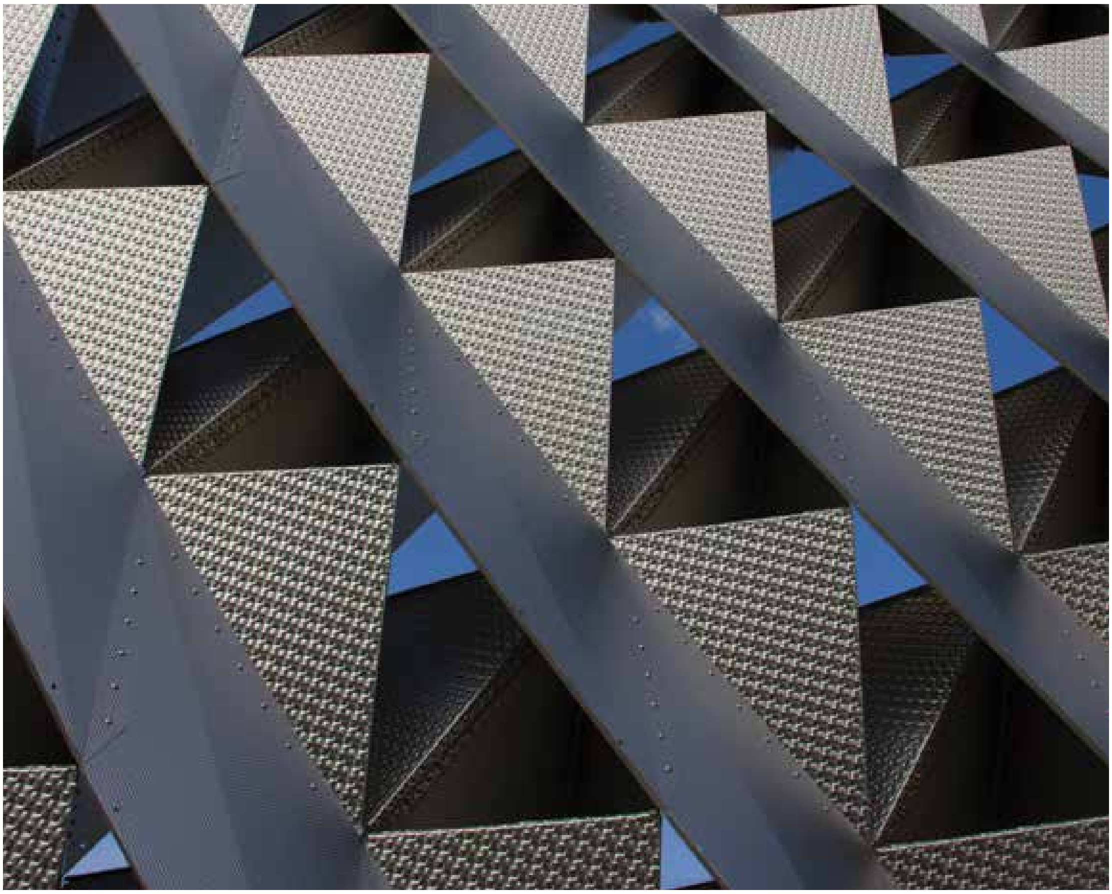


Figure 4: project 2XmT – detail view showing X-braced diagrid with panel-to-panel connection using 10-24 fasteners

exhibits extreme physical and visual lightness (fig. 3). Based on the textural qualities of the metal and the principle of triangulation, specifically through the use of an expanded diagrid, we invented an ultra-thin, woven "face-frame"—a space frame turned into surfaces where, instead of nodes, overlaps in the surfaces make the connection (fig. 4). What is made clear through this work is that the rigidizing process simultaneously creates a visual and structural potency, making large-scale thin-gauge assemblages possible (Picon 2003). At a height of 19'-6" (5.8m), it may be the world's-largest self-structuring surface, and we have speculated that we can use this framework to scale up infinitely (fig. 5).

As an approach, it can be compared to the Los Angeles County Museum of Art's original Art and Technology program, which ran from 1967 to 1971. Curator Maurice Tuchman invited artists to be matched with companies working in industry, pairing Tony Smith with the Container Corporation, a manufacturer of paperboard products including folding cartons, paper bags, and fiber cans. Up until that time, most of Smith's sculptures were generated from modular-based paperboard components, typically tetrahedrons or octahedrons, but the component nature of his work became invisible once the work was fabricated in steel at a much larger scale. Working with the Container Corporation, he could replicate his method of working at a monumental scale—resulting in a 2,500-unit cave-like exhibition for the U.S. Pavilion at Expo '70 in Osaka, Japan (King 2014). As in our case, the installation achieved a more precise level of clarity when artist and industry jointly collaborated on research.

This model of collaboration is closely aligned with a privately sponsored research project, and in the planning stages, it requires a great deal of time to frame the research in a manner that is mutually beneficial to both parties. Working agreements are signed outlining the scope of the research, project expectations are agreed upon, and monies exchange hands to execute the research. From the start, it was clear that it would entail far more oversight from the manufacturer and regular meetings with the fabrication team, and that we would be integrated into their monthly production cycle as if we were a paying customer. As a model, it requires financial support, larger quantities of raw material, and higher demands on machine time and human labor, but if successful, the research would dramatically increase the visibility and marketability of their product line. In addition to the potential marketing benefits, we felt it was equally as beneficial from a technical perspective. The digital tools we were introducing were not part of the day-to-day workflow of the manufacturer, which has since changed as a result of our work and our attempt to demonstrate its relevance in advanced manufacturing. Furthermore, by discussing the project in a parametrically controlled digital model, architects and fabricators are able to speak the same language and clearly visualize information. This three-dimensional conversation allows the fabricators to work off a more accurate base file, reduce mistakes, and thus minimize risk. It also results in better coordination amongst team members and in a faster fabrication schedule than projects of a similar scale/scope. For our team, this digitally-based workflow reinforces our appreciation for mathematics, allowing us to be more creative and explore more complex geometries that were not familiar to the fabricator, thus spending additional time, which would have otherwise been dedicated to project coordination, on design. More importantly, this collaboration allows us access to cutting-edge machinery and the ability to test ideas at a much larger scale than previously possible, re-centering the material mockup as a crucial and necessary part of the architectural design process.

MODEL 3: FACULTY AS CONDUIT

The third collaborative model was a two-day specialized workshop that was part of the 2013 International ACADIA Adaptive Architecture Conference. The workshop covered topics ranging from scripting to simulation of complex systems, to digital fabrication with advanced manufacturers. As workshop directors, we were interested in getting students and professionals to directly interact with the fabrication team, with the primary goal of getting participants on the factory floor with the people who make things, observing the process of how their drawings are translated to generate CNC code that can be read by the machinery available within the facility (fig. 6). For many participants, this is their first time on a factory floor exploring a type of making that is unfamiliar to them: making with machines. At a minimum, we wanted participants to understand how to effectively communicate with fabricators.

Throughout the two-day workshop "Rigidized Metal Forming," we were tasked with consolidating what we had learned in one year into a 48-hour period, taking students through the entire design-to-fabrication process. Participants were consistently moving between analog and parametric ways of thinking/making, trying to live in both of these worlds simultaneously and realizing a very small but critical lesson, as stated by the French engineer Robert Le Ricolais: "The art of structure is about where to place the holes." Even in a very brief period of time, the opportunity to speak directly with fabricators, tacitly handle the metal, and assemble a prototype of their own design changed the way participants thought about material and fabrication (fig. 7). In addition, the manufacturer's affiliation with the ACADIA community gave its product wide exposure both domestically and internationally by supporting students, academics, and professionals from around the world. The workshop model is an effective method for closing the gap between the academy and the profession, and perhaps more importantly, breaks from the traditional university model that is comprised of 15-week academic semesters with classes meeting once or twice weekly. From our experience, the workshop model, based on brief but uninterrupted periods of intense learning, is able to produce similar results in terms of output and quality when compared to typical university coursework, such as described in Model 1.

MODEL 4: FACULTY AS TACTICIAN

The fourth model of collaboration was a repeat of the latter half of Model 2 (Faculty as Material Scientist), except that it was now a long-distance collaboration amongst many parties involving a commissioning agent serving in the role of client, a number of universities that make up the TEX-FAB Digital Fabrication Alliance, A. Zahner Co. as fabrication sponsor, and an additional engineer. The project needed to be completed in a matter of weeks, not months; thus, we saw ourselves in a new role—that of tactician, with a large majority of our time and energy dedicated to managing the relationships between a greatly expanded team of stakeholders. An added challenge was that this research would have to be conducted remotely with very little face-to-face communication, which was vital to the success of previous models.

As part of our TEX-FAB SKIN competition winning entry, *project 3xLP*, we were granted the opportunity to build a second iteration of our SKIN prototype, refining and experimenting with our self-structuring system to introduce visual porosity while maintaining structural stability (fig. 8). Our first assignment was to negotiate bringing Rigidized Metals on-board as both a co-material and co-fabrication sponsor. This strategy allowed us to continue to work with a material that we felt was central to the research, and not knowingly, more than double the funding available to execute the second prototype—thereby increasing the scale/scope of the second prototype. With little time to build physical prototypes, we opted to digitally simulate the effect of physical forces with the assistance of Maria Mingallon, a structural engineer at ARUP, performing an initial round of FEA analysis on the second prototype, creating a feedback loop between digital model, our first physical prototype, and stress-based FEA analysis (fig. 9). Stated Mingallon, "The results of the digital analysis demonstrated that the origami-like strategy would make the wall strong enough to deal with the typical design loads applied to medium-height buildings" (Mingallon 2014). This feedback provided a level of confidence that we could apply our system at a much larger scale and as a contemporary facade solution.

As mentioned above, this collaborative model was

about speed, expanding outreach, and relying on external expertise to complete the project. There was little time to meet in person, to design, to prototype, and most importantly to make a mistake. In doing so, our three-dimensional modeling got tighter, containing more precise data regarding part numbers, geometric families, patterns, gauges, grain, finishes, and assembly sequence (fig. 10). Our need for traditional drawings was dramatically reduced (not eliminated), resulting in labor being spent on iteratively testing design solutions and resolving details to achieve tighter fabrication tolerances. We also began to optimize design parameters to find a suitable balance between geometric variation, machine time, and human labor (fig. 11). The competition platform provided a showcase to demonstrate the fabrication capacity of two expert manufacturing companies. Repeating the process strengthened and solidified our working relationship with RMC, a world leader in deep textured metals, and also allowed us the rare opportunity to collaborate with A. Zahner Co., a world leader in metal facade manufacturing. From a marketing perspective, the benefits were noticeable, as the results were included in various print/online publications and numerous contacts were made within Texas.

Figure 5: project 2XmT – elevation view of 19'-6" tall, 152-panel self-structuring prototype using 4LB and 1RL rigidized metal

MODEL 5: FACULTY AS PROCESS ENGINEER

The fifth model of collaboration is a joint-venture partnership forged between a public research institution and a privately held company—one focused primarily on the development of large-scale, modular building structures and the other, primarily on the development of innovative building skins—whose collaboration attempts to further develop a more marketable product that could be more widely distributed in global architectural contexts. In early conversations, both parties were interested in forming an interdisciplinary partnership that would merge the two threads of research together to form a more holistic system that could deliver architectural solutions for both structure and skin.

The authors teamed up with Bartolomeo Mongiardino and Alessandro Traverso, mechanical engineers based in London, England, and inventors of the Absolute Joint System (AJ), one of two non-welded, round pipe, stainless steel structural systems in the world. More specifically, AJ is a dismountable and reusable space frame system with members connected by means of custom spherical joints (fig. 12). Targeting reusability in lieu of recyclability, the AJ system is a highly durable kit-of-parts for small to large scale space frames that can adapt to a wide range of spatial configurations to reduce waste and minimize the embodied energy required to create building structures (Brescia et al. 2013). Our collaborators examined that there is an increase in the production of temporal programs that require large expanses of column-free space, such as temporary shelters, storage/transportation facilities, and large stadiums,

Figure 6: Rigidized Metal Forming workshop – participants observing drawing-fabrication process at Rigidized Metals Corporation as part of the 2013 ACADIA Adaptive Architecture Conference

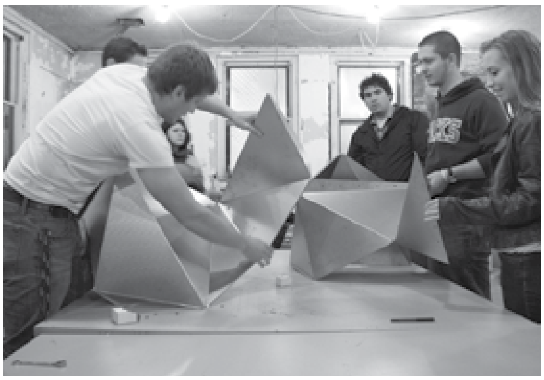


Figure 7: Rigidized Metal Forming workshop – participants assembling their 5-7 panel prototypes using 3ND rigidized metal as part of the 2013 ACADIA Adaptive Architecture Conference

whose intended lifespan may be shorter than traditional buildings. In contrast to the costly maintenance and (oftentimes) inaccessibility of these permanent structures, the dismountable AJ system proposes an alternative.

In response to the agenda set forth above, we summarized our work very broadly, working simultaneously in three areas to increase the feasibility of the AJ system, troubleshoot the existing web-based product offering, and testing its structural system against a range of geometries, enclosure systems, and panelization options. Currently, we are focusing on the development of surface optimization and efficient panelization using rigidized metal that can adapt to multiple configurations (fig. 13). Similar to the concept of the AJ system, we are attempting to develop a series of identical panel families that can be applied to formally distinct free-form surfaces. By designing a kit-of-panels, we are attempting to construct a full-scale mock-up that explores reusability in large-scale architecture: a reconfigurable kit-of-parts, structure and skin, that can be mounted and dismounted, packed in a shipping container, shipped across the globe, and reconstructed in a range of configurations.

For our team, this work has many benefits. It is research that directly engages in the construction industry and develops solutions that find efficiencies in problems that have existed within the discipline for decades. In addition, it allows our work to move toward a marketable product that could very quickly reach a global audience, doing so at a large-scale. For RMC, it is an ideal application for its deep-textured products: lightweight, durable, and highly resistant to visible scratching, they become ideal for structures that are repeatedly assembled and disassembled. For the AJ team, our collaboration gives them a base of operations in the United States, a manufacturing partner in RMC, and the ability to test their system on a range of complex geometries prior to entering into the highly competitive material manufacturing market.

MODEL 6: UNIVERSITY AS INCUBATOR

In this last model of collaboration, our role shifts from faculty-directed research to that of architectural consultant with workflow moving through the manufacturer. In the contemporary AEC industry, there is a reoccurring pattern where clients are looking for the manufacturer to provide in-house expertise to solve technical and logistical issues that arise throughout the design and implementation process. As the research moves from sponsored to for-profit commissions and consultations, we have found a usefulness for a young design practice that can move fluidly between a design-assist and a design-led format depending on the scale, scope, and scheduling of an incoming project. When not acting in a traditional architectural role, we operate as an alternative mode of practice, hovering between academia and industry and able to provide a number of alternative benefits: mediating between architects and manufacturing throughout all phases of the design process; teaching sales and marketing teams about emerging trends in architecture; and focusing on commissioned work that exists somewhere between the scale of furniture and architecture. This newfound capacity allows RMC to take on work it would have otherwise turned away, thereby increasing internal capacity and allowing a greater audience access to its product offerings. In this scenario, both university and industry-supported work generates an incubator where young design practices can balance their intellectual curiosity with 75 years of industry expertise.

CONCLUSION

This paper has focused on relationships that faculty within the University at Buffalo Department of Architecture have been forging with local industries, and how this is leading to practice models that hinge on developing material and data-driven research in the academy, testing and applying these developments in industry, and forming feedback loops between the two. From this categorization process, we have come to understand our work within the various models of research and practice listed below:

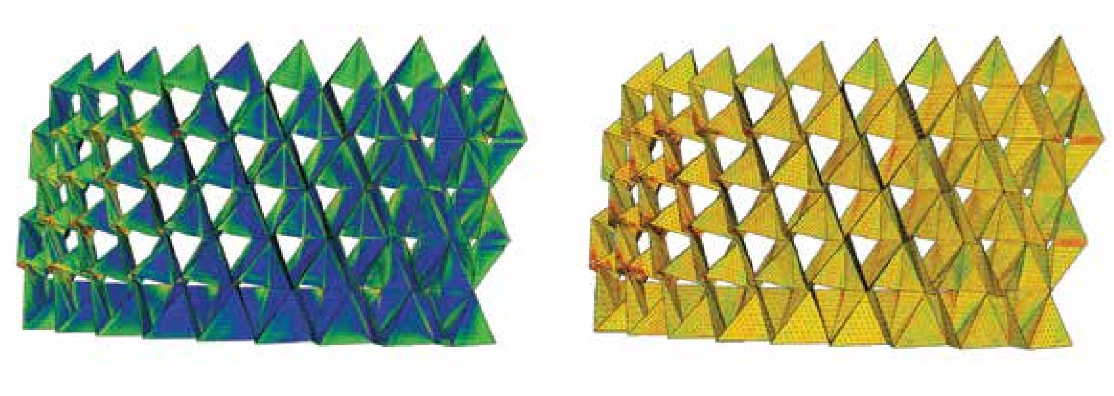
Model 1: A description of faculty as project initiators or organizers—instigating curiosity among students, encouraging a curriculum that engages students in a deeper knowledge of material, and facilitating student/professional relationships—not only with other architects but also with manufacturers and fabricators.

Model 2: A description of faculty as material scientists—engaging in research through making that attempts to teach new technologies to manufacturers and test the latent potential of materials by building prototypes that maximize material performance, exploit structural and specular qualities of textured metals, and push the limits of manufacturing tolerance.

Model 3: A description of faculty as a conduit between students and manufacturers—leading to an academic environment where acquiring a "deep knowledge" of materials through hands-on work is more of a norm than an exception.

Figure 8: project 3xLP – interior rendering prepared for TEX-FAB SKIN Competition showing application of our geometric system as a building skin with increased visual porosity

Figure 9: project 3xLP – FEA analysis (wind load and permanent load) of SKIN prototype using ARUP's structural analysis software Oasys GSA



Model 4: A description of faculty as liaison or tactician between businesses to implement a project—focusing on managing the multiplicity of relationships amongst an expanding group of stakeholders.

Model 5: A description of faculty as process engineer—serving as a design-laboratory to test-drive new technologies and new tectonic solutions prior to entering into a competitive market.

Model 6: Thinking more broadly about the university as an incubator of young practices whose design professionals can act as a mediator between manufacturers and architects.

In conclusion, these are models that we are exploring as alternative modes to traditional architectural practice. The models suggest that these are not idiosyncratic moments/relationships, but rather, educational, research, and practice models that can be replicable in other locations and with other companies, and sustained for the long-term. Although each of these is capable of being a standalone model, they can be performed in succession as a relationship-building strategy, or they can simultaneously overlap, where one model can serve as a test-bed for the other. Nonetheless, it is through initiating a conversation about computation-tied-to-making that we are able to directly engage in the supply chain, allowing architects and manufacturers to develop a collective intelligence and a highly collaborative workflow. Through the use of these organizational models, parametrically controlled three-dimensional modeling, and an extreme attention to detail in the manufacturing process, we argue that we are increasing the scope of architecture—taking control back into the realm of the architect and reconstituting the legacy of the master-builder. It is this confluence of interest in both digital technology and contemporary industry that has offered us a way to push forward an alternative trajectory of architectural research and practice.

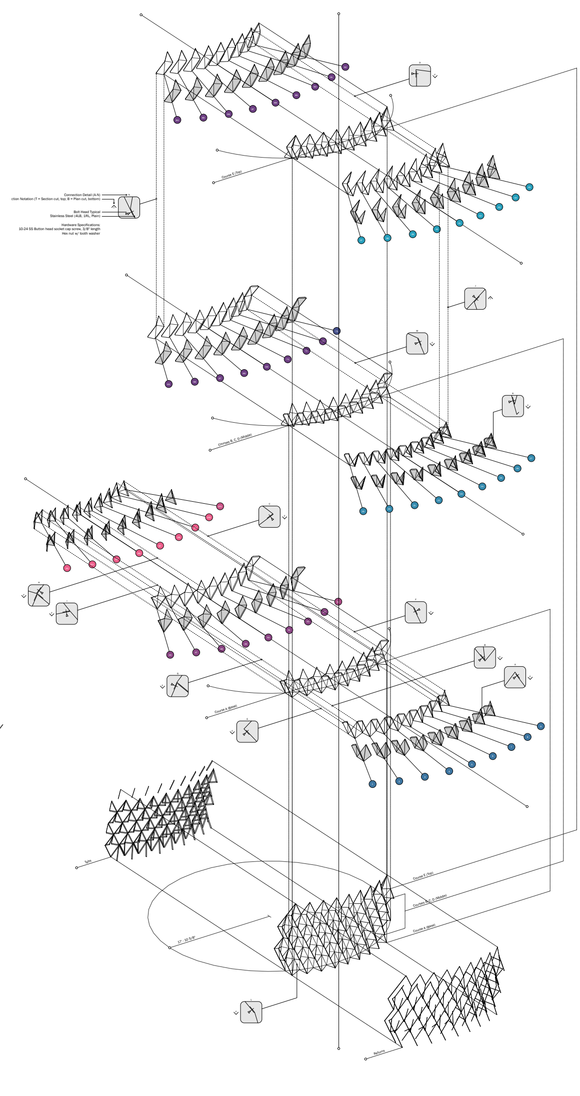


Figure 10: project 3xLP – exploded axonometric of 10'-6" tall, 137-panel self-structuring prototype showing course-by-course system coordination/ optimization

Figure 11: project 3xLP – detail view of SKIN prototype showing geometric variation, visual porosity, and specular qualities using 4LB and 1RL rigidized metal along with angel hair stainless steel manufactured by A. Zahner Co.

Figure 12: AJ Pavilion – concept rendering of AJ structural system showing non-welded custom node

Figure 13: AJ Pavilion – screenshot of preliminary free-form surface showing optimized panel clusters

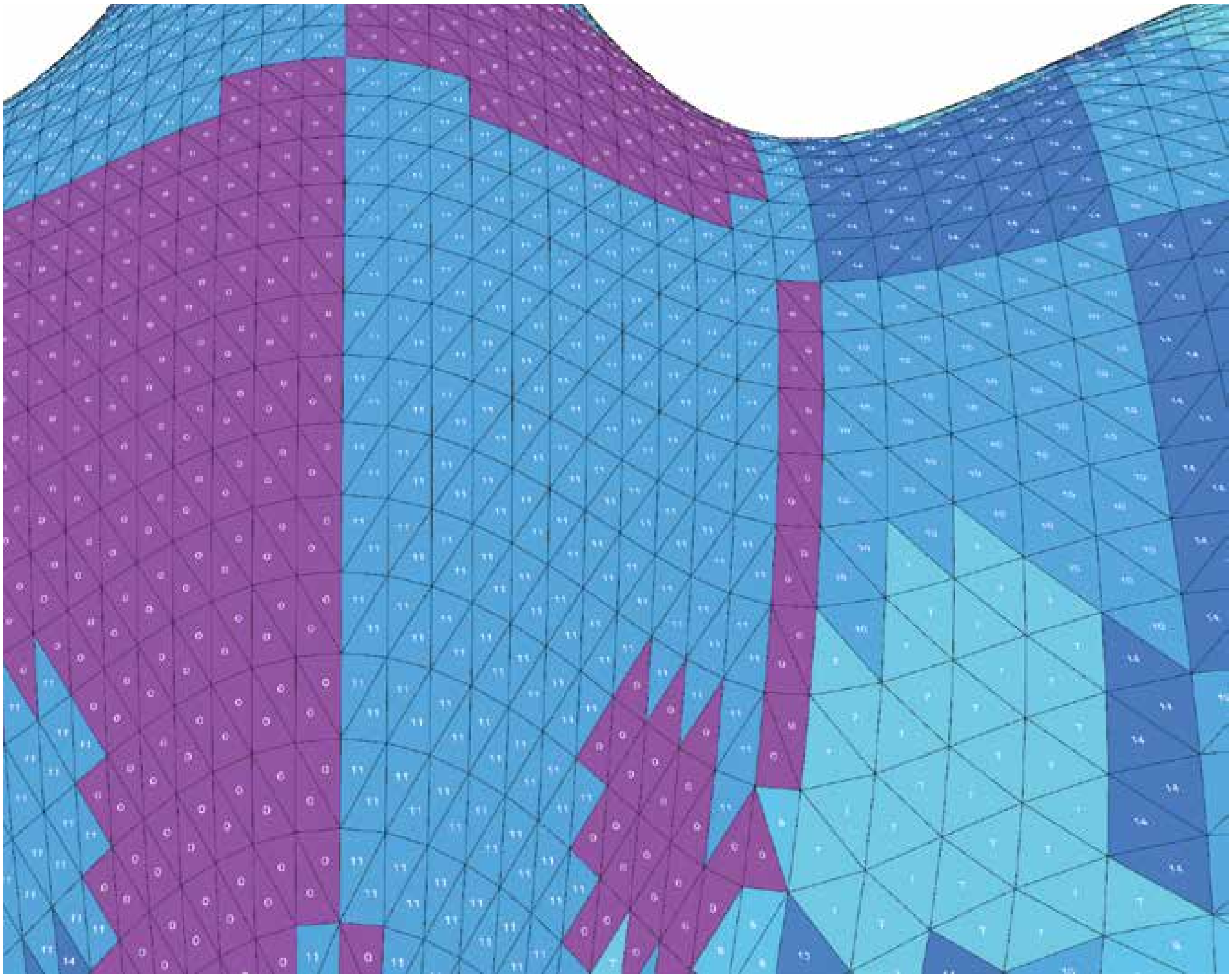


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IMAGE CREDITS

All images credited to the authors: Bruscia, Nicholas and Romano, Christopher (2014), except Figure 9, credited to Mingallon, Maria, ARUP, 2014, and Figure 12, credited to Mongiardino, Bartolomeo and Traverso, Alessandro, Absolute Joint System, 2014.

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Generative Techniques for Mass-Customized Form: Samsung Raemian Housing Masterplan, Haan River, Seoul, Korea

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The Raemian brand was launched within South Korea's apartment industry by Samsung C&T in 2000, to create comfortable, futuristic living environments for city dwellers. Raemian masterplans repeat quantitatively different floor plans in different building typologies ranging from a Flat-Type to an A-Type. At the outset, the buildings all looked the same, so much so that if you drove past them, the only distinguishing feature from one to another is a serial number painted on each building in the masterplan development.

This cost-effective practice lasted until 2009, when the mayor of Seoul wrote into law that if there were more than two buildings on the same development site, they must be distinguishable from each other. Initially, developers circumvented this decree by altering heights of buildings while keeping the same aesthetics, due to cost-saving measures. Later the ordinance was clarified to include the requirement of a change in the look and feel of each building. At this time the largest construction company in Korea, Samsung needed assistance in devising a cost-effective alternative that could adhere to the strict rules of plan configurations with variations in the nature and type of buildings.

Contemporary Architecture Practice (CAP) provided such an alternative. In addition to utilizing all of Samsung's research on housing within Seoul's strict zoning regulations, the practice made use of its own knowledge of writing a design program in C++, as well as of knowledge that it had previously developed with Wharton Business School to calculate costs for different masterplan configurations in real-time. Once the C++ system was developed to include all quantitative regulations, CAP elaborated a design component that worked well within the limitations of the Samsung design strategies, deploying their manufacturing techniques.

This interface set the limits of the amount of variation possible within buildings, yet allowed the possibility for there to be enough variation, and hence customization, in each. What became apparent is that the integration of the Samsung component logic generated the maximum profit for the housing associations that constituted the clients, yet also yielded qualitative difference between buildings. The interface, its design, and the logic of its mechanisms to generate outcomes on the scale of the city are

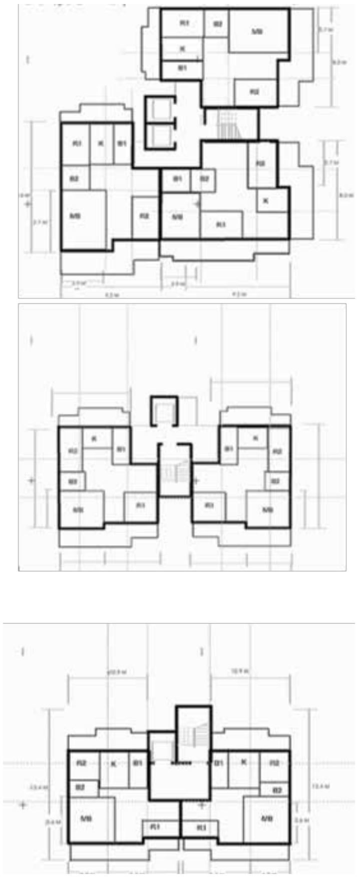


Figure 1: Due to the push for standardization in housing, the scale and size of the unit is the only attribute that is different from one housing development to another. The size is determined based on the tax structure for the scale of apartment unit, ranging from 59.99 square meters to 119.99 square meters.

inherently laced with CAP's desire to develop configurations which align with the practice's formal interests. The design research and the C++ generative system convinced Samsung that CAP's method was accurate enough for them to quantify the results, and that these results were reliable. Once this had been achieved, CAP put the system through a tremendous amount of testing under the auspices of the Research and Development Group at Samsung, using it to develop a masterplan comprising 18 high-rise buildings, together with the designs for each individual building. The masterplan incorporates all the programmatic and zoning codes required to maximize views and quality of light within the mid-highrise development. The proposal reassesses the value of a central recreation area for the entire community, and develops several microcommunities around smaller zones for recreation.

The advantages of this approach include the ability to provide variation within a microcommunity, as well as throughout the overall masterplan, through different qualities of buildings and landscapes. The structures adhere to strict building regulations, such as those on unit size, while maximizing the amount of variation of views and interior space within the plan configurations. This was determined primarily by the locations of all the buildings' vertical systems, including the circulation as well as dry and wet shafts. The building panels and glass are flat, yet they articulate movement across the facade, enriching the project form. Each unit affects the location of the adjacent units in each of the buildings, thus eventually developing a masterplan with a look and feel based on floor-by floor regulations and repeatable customized components in its manufacture, instead of typically mass-produced building-to-building relations only. The proposal re-assesses the value of a central recreation area for the entire community and develops several microcommunities around smaller zones for recreation. Benefits are gained, including the ability to provide variation within a microcommunity through different qualities of buildings and landscapes, as well as within the overall masterplan. The buildings adhere to strict building regulations, including as to the size of the unit, while maximizing the amount of variation of views and interior space within the plan configurations. Each unit within the building affects the location of the unit in the building next to it and so on, eventually resulting in a masterplan with a look and feel based on floor-by-floor regulations and repeatable customized components in its manufacture instead of typically mass-produced building-to-building relations only.

In summary, the Haan River masterplan was developed using a complex system of rules and programming code that generates masterplan opportunities which adhere to all the required regulations in minutes. Previously, these plans would take an architect a year to design, and always led to homogeneous outcomes. CAP's system adds value for the client, as all the pressures of codes and cost are taken into account at the beginning of the design process, enabling the development of a nuanced and elegant masterplan with innovative buildings using cost-effective variation that is mass-customized.

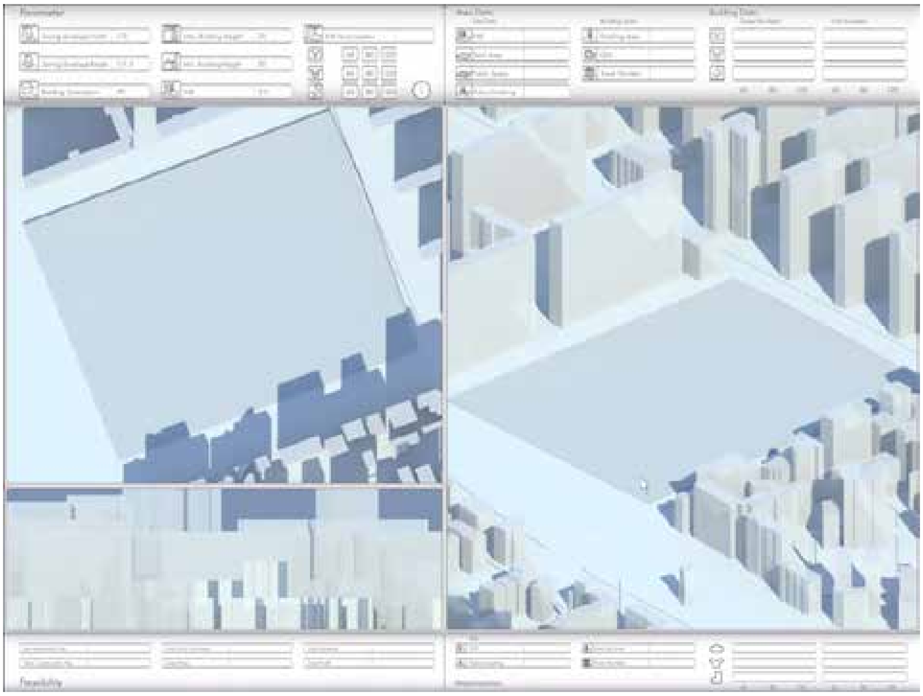


Figure 2: Generative software. The software was developed over a year of research after understanding the Raemian System that Samsung has developed, which created their dominance in housing in Seoul, Korea. The generative system takes into account all the building typologies, as well as housing unit sizes, and integrates this information with all the regulations to develop accurate masterplans that maximize floor area ratios. What is apparent in the system is that the coding actually designs the distribution of the masterplan. Hence, our goal was to adhere to the strict rules and logics that Samsung provided us and combine it with our design intentions.

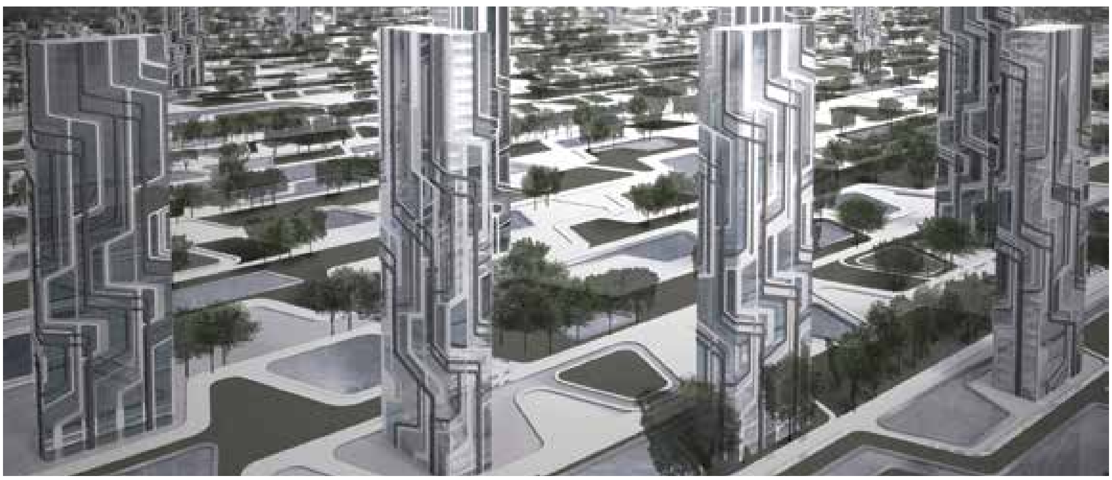


Figure 3: Haan River Masterplan. Our system is able to generate as many buildings as physically possible on the site to maximize floor area ratios. The configuration shown was the basis of the 18-building masterplan that we went on to develop.

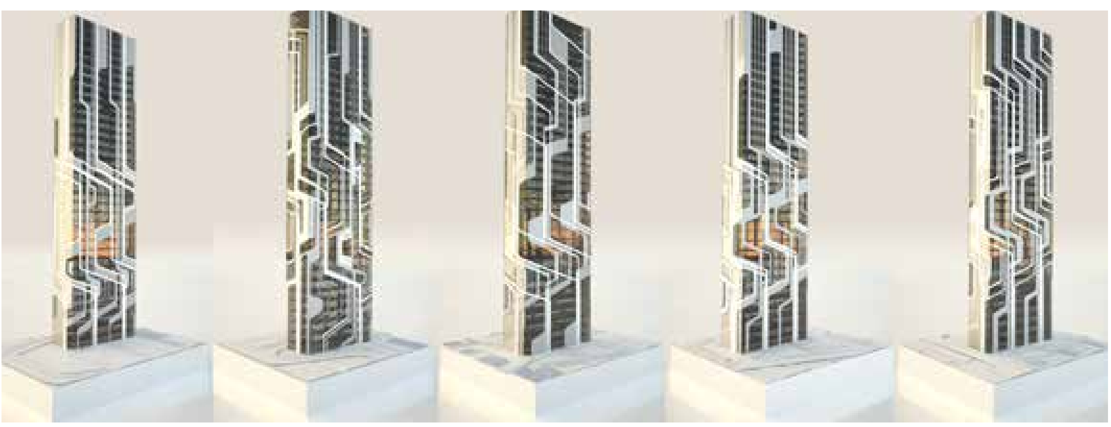


Figure 4: Building variation. The buildings are different yet related. We developed the greatest variation within the given parameters of regulations, determining the overall form of the masterplan as well as each building. We had to maintain the costs within an acceptable framework for the client, which required us to work within the levels of customization afforded to us by Samsung construction.

Figure 5: Haan River Masterplan, axonometric view. A system of relations based on unit-to-unit distributions in addition to the normative building-to-building regulations allowed for a system of variation.

Figure 6: Building design. A three-dimensional prototype of a building contained within the masterplan showing the inflection of form due to interior spatial configurations, vertical alignments, and maximal variations permitted within Samsung building components.

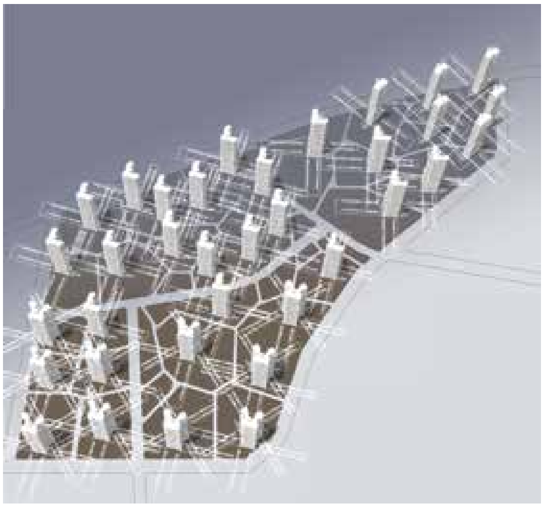
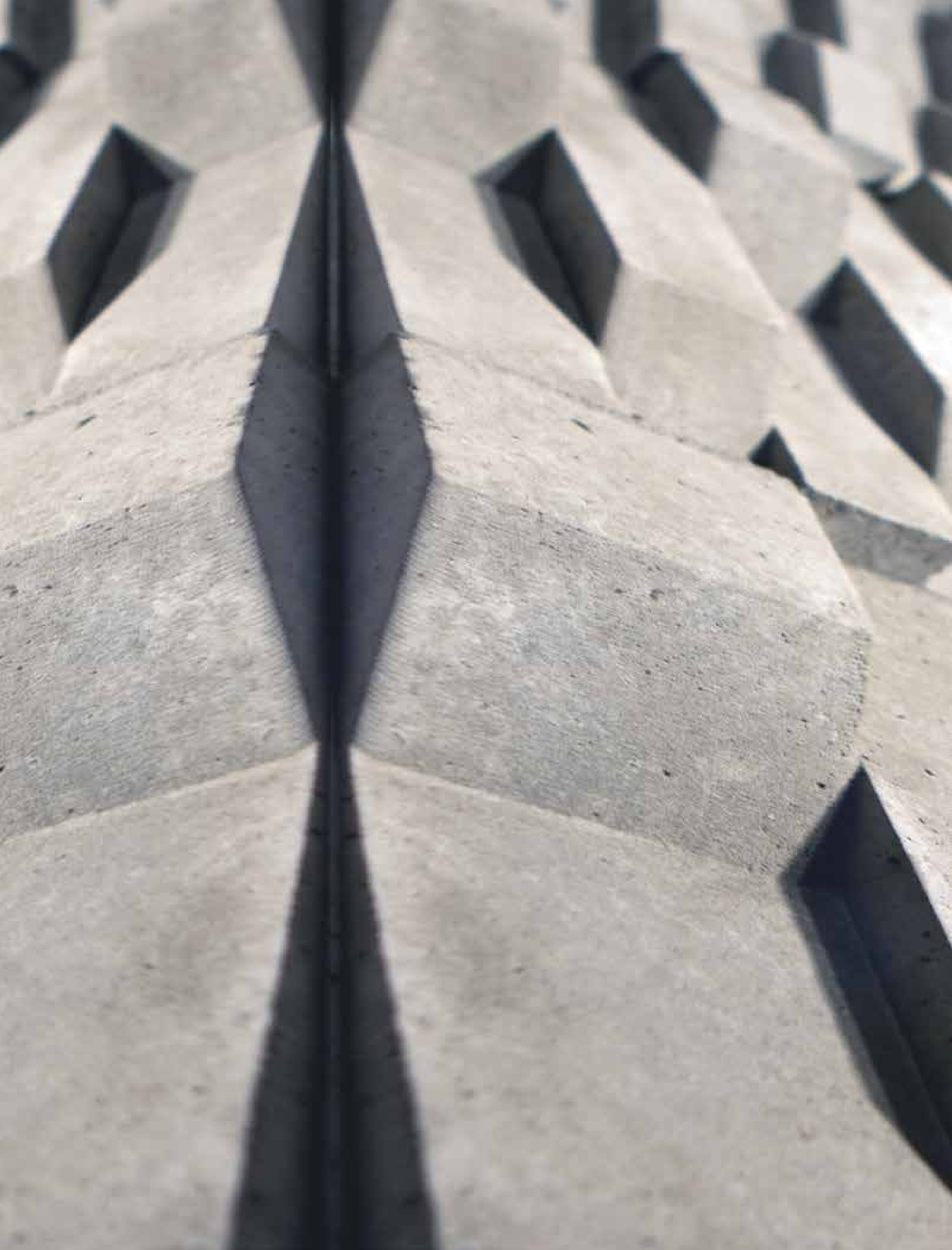


Figure 7: Masterplan view. The qualities of the masterplan distinctly differ from the typical housing development in Seoul. The efficiencies of mass production are circumvented for mass-customization in the production of large-scale building populations within cities.



Visualizing Thermal Morphologies

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Figure 1: Concrete thermal patterns generated while constrained by the same volume and controlled increase of surface area. Epiphyte Lab, 2014.

Architects have historically circumvented the need within the design process to establish real-time or sensor-based feedback relationships between the object and its environment by avoiding the complex variability of the actual environment. This has been accomplished by using a reductivist approach that takes large sets of spatial and temporal data, deriving mean values, and using these "average" conditions to inform both design goals and processes. Such a method understates the causalities across the systems and fails to engage the relevant information of the nuanced performative realities. The concreteness of the actual gets lost in the abstraction of the interpolated ideal. Given the lack of computational tools that can simultaneously integrate both analysis and design scenarios, this method once made sense. However, the current trend in building simulation research leans toward deciphering the specific causation of performative variability within high-dimensional parametric spaces.[1] Such methods can serve as means to successfully expose discrete and dependent relationships between environmental variables, spatial organizations, and other forces, and can highlight the need to develop a design methodology that incorporates dynamic feedback that enables the testing of multiple scenarios for the production of design intent.

In a time when digital tools outpace design methods, we now see an increasing emphasis on providing empirical support for a historically qualitatively-oriented profession; there is a need to develop a research framework that allows for a more comprehensive

Figure 2: Samples of proposed surface geometries.

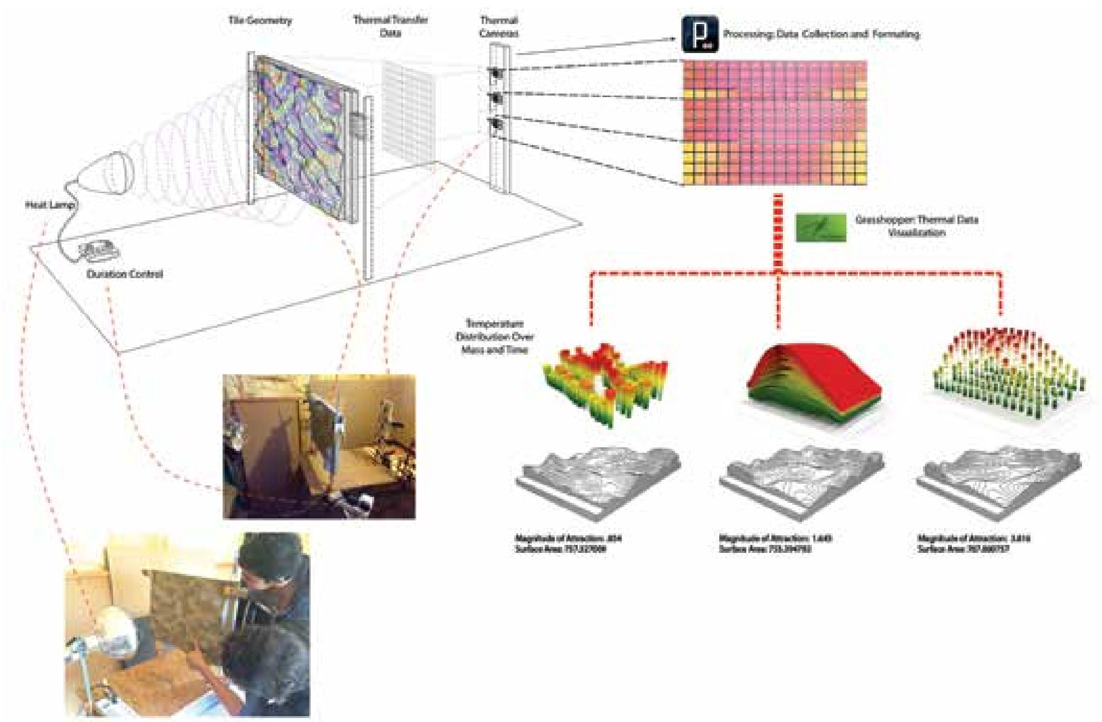


Figure 3: Diagram of physical simulation process and thermal data collection and digitization.

assessment of both context condition and design effect. Today, with plugins like Grasshopper (GH) for Rhinoceros 3D,[2] designers are able to integrate data and computation within their native modeling environment. Furthermore, the ability to couple information with geometry and dynamic visualizations enables the potential to produce intuitive and informative representations of data that is otherwise esoteric when confined to a numeric format. Our thermal mass research project (fig. 1) provided a case study in these contemporary methods: We tested the extent to which the incorporation of data processing within a visualization environment is able to provide intuitive representation of complex information, comparing thermal metrics against desired effects.

The Thermal Mass Regimes[3] project investigates the impact of complex geometry on the process of passive heat distribution in thermal mass systems (fig. 2), with the goal to develop design principles that effectively engage the thermal gradient between buildings and their environment. These processes and goals necessitate a deeper understanding of how specific morphological manipulation of mass distribution to surface area affects the rate of thermal transfer, and how the surface area geometry can become an operative design variable in energy collection, throughput, storage, and re-radiation of sensible heat. The analysis of our geometric populations suggests the possibility for a more synthetic incorporation of morphology, one in which surface geometry can be passively utilized to generate playful effects, while providing more fidelity over the pace of thermal absorption and release of sensible heat.

Our methods utilize workflow that connects parametric tools with raw thermal data from physical simulation in order to analyze and visually represent thermal performance of unique geometries. Custom scripts for interpretation and representation of data help translate large sets of information into approachable formats that offer intuitive application of complex information.

Globally, the Mass Regimes project defines principals that integrate passive-system thinking into the built environment. By understanding thermal behavior in response to the scale, form, and color of architectural components, we begin to define new design strategies and, from them, design solutions that respond to multi-variable parameters. This process thus aids in the negotiation of balance between thermal functionality and immersive experience. The knowledge thereof expands design possibilities while empowering the building surfaces with self-regulating properties and reducing the building's dependency on mechanical systems.

The main reason that thermal passive strategies are not used more extensively in design is that the traditional Trombe[4] and mass systems ask for solid concrete mass, generally blocking light and views while failing to create an appealing space within. We are interested in establishing a synthetic design response to thermal and aesthetic criteria by developing a specific functional thermal mass pattern logic that allows for apertures within its surface.

In the Mass Regimes, we physically simulated the thermal behavior of 30 tiles (fig 3). This set was made up of five families of six concrete tiles measuring at 16" x 24". The ratio of volume to surface area is a functional performative parameter that contributes to effective convection. The tile geometries were generated using the Galapagos[5] genetic algorithm solver to ensure consistent volume across all tiles while increasing the tile surface area within each family (fig. 4).

In the physical simulations, the tiles were exposed to a heat source that was turned on for six hours and then turned off for six hours, heated up and then naturally cooled over a total period of 12 hours. Thermal data was collected by thermal cameras scanning the back surface of the tiles at one-minute intervals. This produced a vast numeric dataset that could be spatialized and interpreted using the computational and graphic powers of the GH plugin for Rhinoceros 3D from McNeel.

The following process is based on interpretation and application of statistical data within system design thinking. Our workflow consisted of four phases: initial data visualization for thematic understanding; statistical processing for taxonomical understanding of performance; defining querying system for desired thermal attributes; and redistributing the pattern and matching the thermal attributes with desired performance and effect.

The GH plugin offers two critical capabilities that enabled us to tightly couple the statistical feedback to the design process. On the most basic level, there is an ability to associate all numerical information directly with 3d geometry, thus allowing for intuitive reading of object performance. Then, by attributing statistical values to virtual objects, the attributes can be used to re-map the objects onto newly designed systems: Conditioned by another layer of information, this "reception" map outlines performative desire and receives the trending pattern. Such a process requires that steps and feedback loops be constrained by the same statistical parameters in response to systems conditions. The level of abstraction necessitated by this process may seem hindering at first: These constraints encouraged the development of an intermediate associative mapping system, enabling the designer to identify numerical values through color and pattern to maintain an understating of the process's input and output parameters.

THEMATIC UNDERSTANDING OF DATA

Collected base thermal data is first exported from the physical experiment in JSON[6] format. This data set represents the temperature of each pixel of the thermal camera at one-minute intervals, in a text-based format. The first operation is the reorganization of the data set according to its four dimensions: temperature, x, y, and time. Figure 5 shows the base 2d representation of the data utilizing a matrix to display time.

Within the GH environment, time, as a fourth dimension, can also be represented in motion as video or, abstractly, as a slider along which one can query specific instances (fig. 6). These representations offer a thematic understanding of how each tile performs uniquely across time and space, and shadows of thermal trends among tiles and families start to become apparent.

STATISTICAL PROCESSING FOR TAXONOMICAL UNDERSTANDING OF PERFORMANCE

The next phase generates and displays each tile's performance statistics in histogram/dot-plot format, as well as in pairwise scatterplots. The goal of this step is to classify all the tiles into performance-based groups. The value here is twofold: First, we gain deeper understanding of the morphologies' impact on thermal performance. Second, we gain a data set embedded within the virtual morphological objects, each with its own series of performance attributes. Once we have written a script to generate all the population parameters regarding tile performance, and have created standard scripts that will process the data into a visual format, we are able to compare, query, and categorize the data in many ways. The matrix in Figure 7 demonstrates different types of information and groups of relationships produced in order to better understand the relationship between surface area, morphology, and thermal performance.

This matrix of data enables the designer to readily engage with each pattern tile or tile family to derive the functional parameters based on performance needs, such as rates of thermal gain and loss, etc. By processing and re-representing our data sets within the GH plugin, we are able to produce more tangible interpretations for designers unfamiliar with conventional statistical meth-

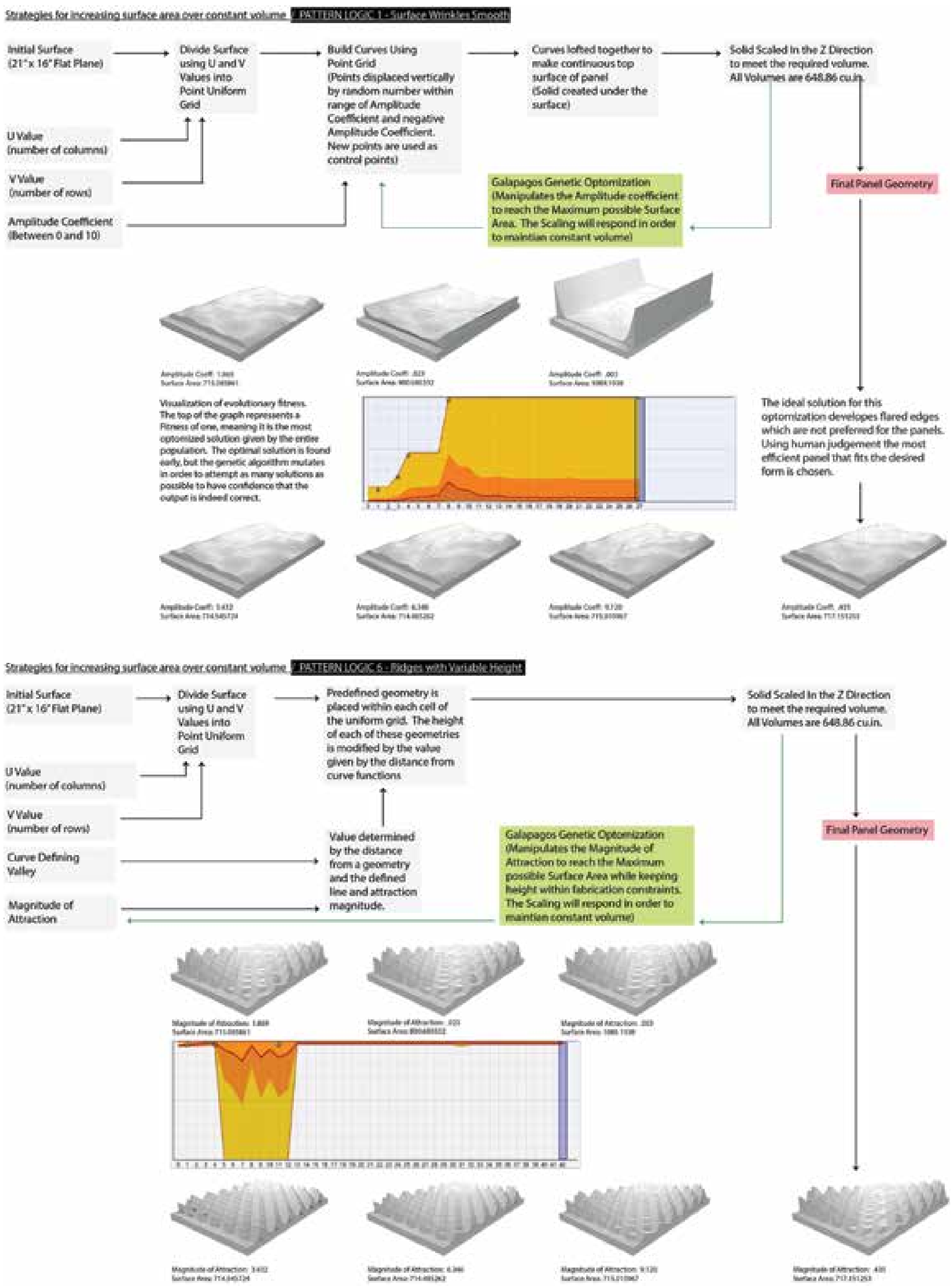


Figure 4: Diagrams of parametric geometric operations – Genetic optimization algorithms for two different pattern logics. Epiphyte Lab, 2014.

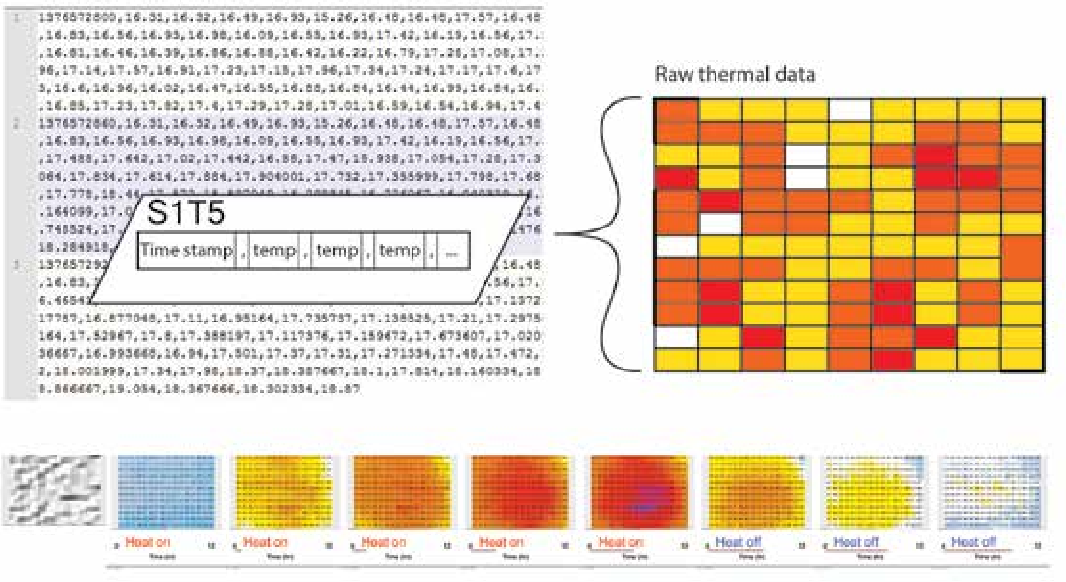


Figure 5: Diagram illustrating raw data translation into color-coded thermal maps. Epiphyte Lab, 2014.

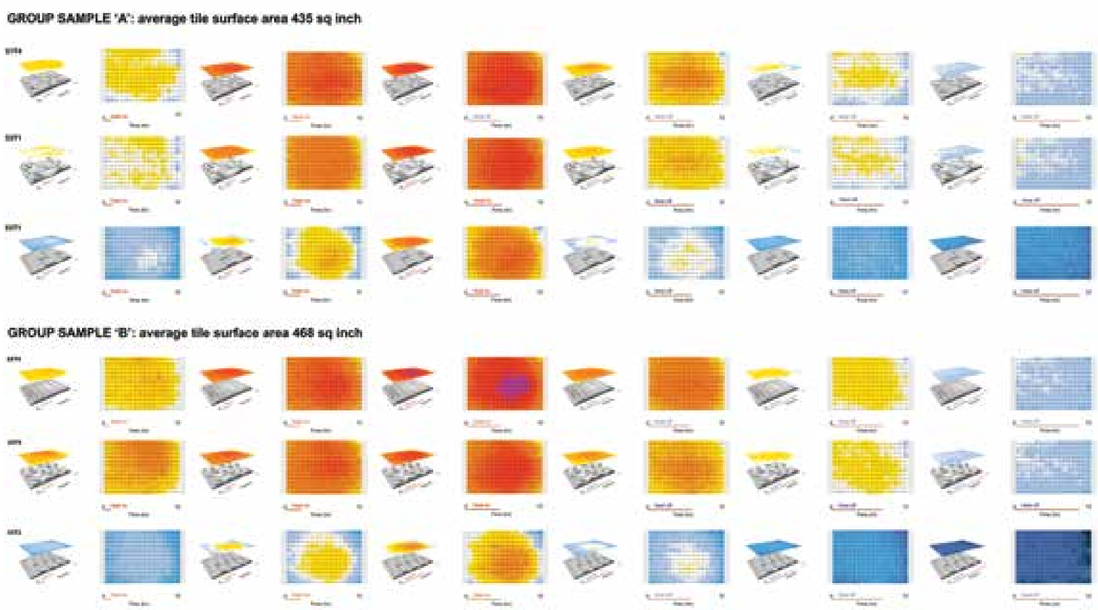


Figure 6: Animated Heap Maps – Sample key-frames from two sets of tile groups with the constant volume and surface area, but with varying surface morphology, visualizing the difference in thermal performance over time. Color-coding refers to the temperature range from approximately 14 to 32 °C. Epiphyte Lab, 2014.

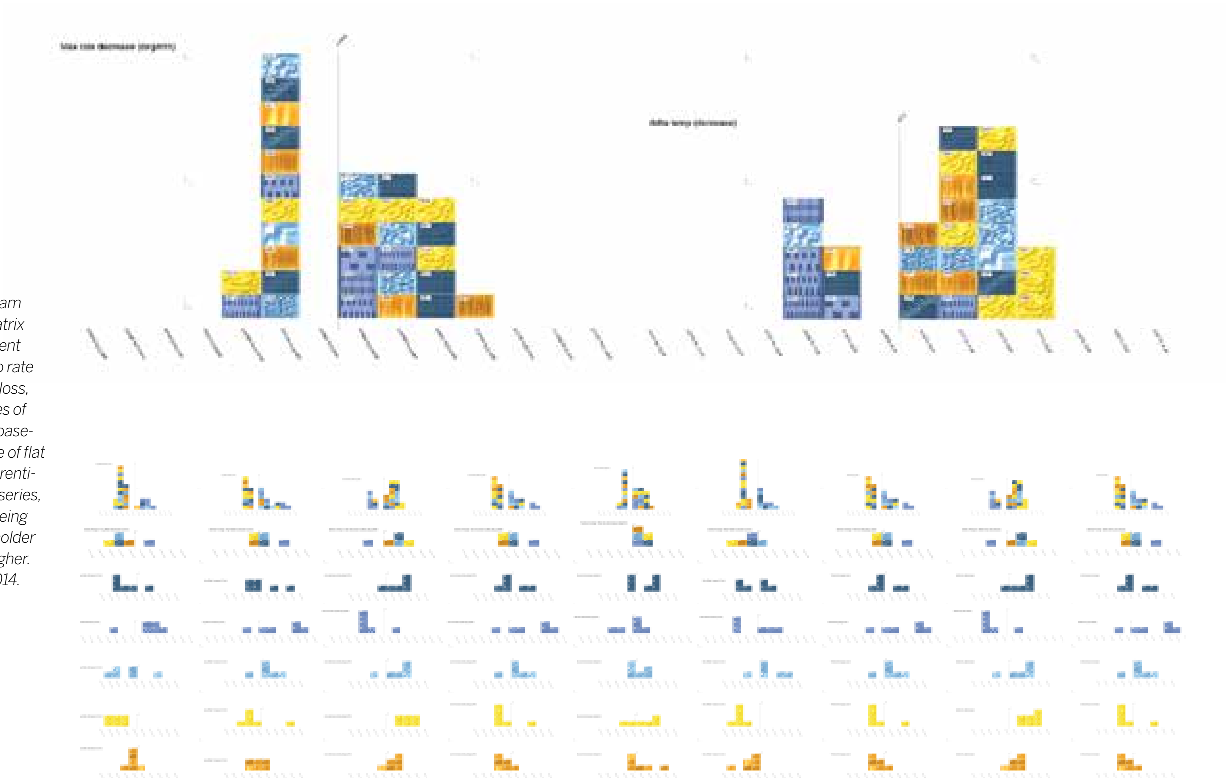


Figure 7: Histogram Performance Matrix – Showing different criteria related to rate of heat gain and loss, sorted by degrees of difference from baseline performance of flat tiles. Colors differentiate between tile series, warmer colors being smoother tiles, colder colors being rougher. Epiphyte Lab, 2014.

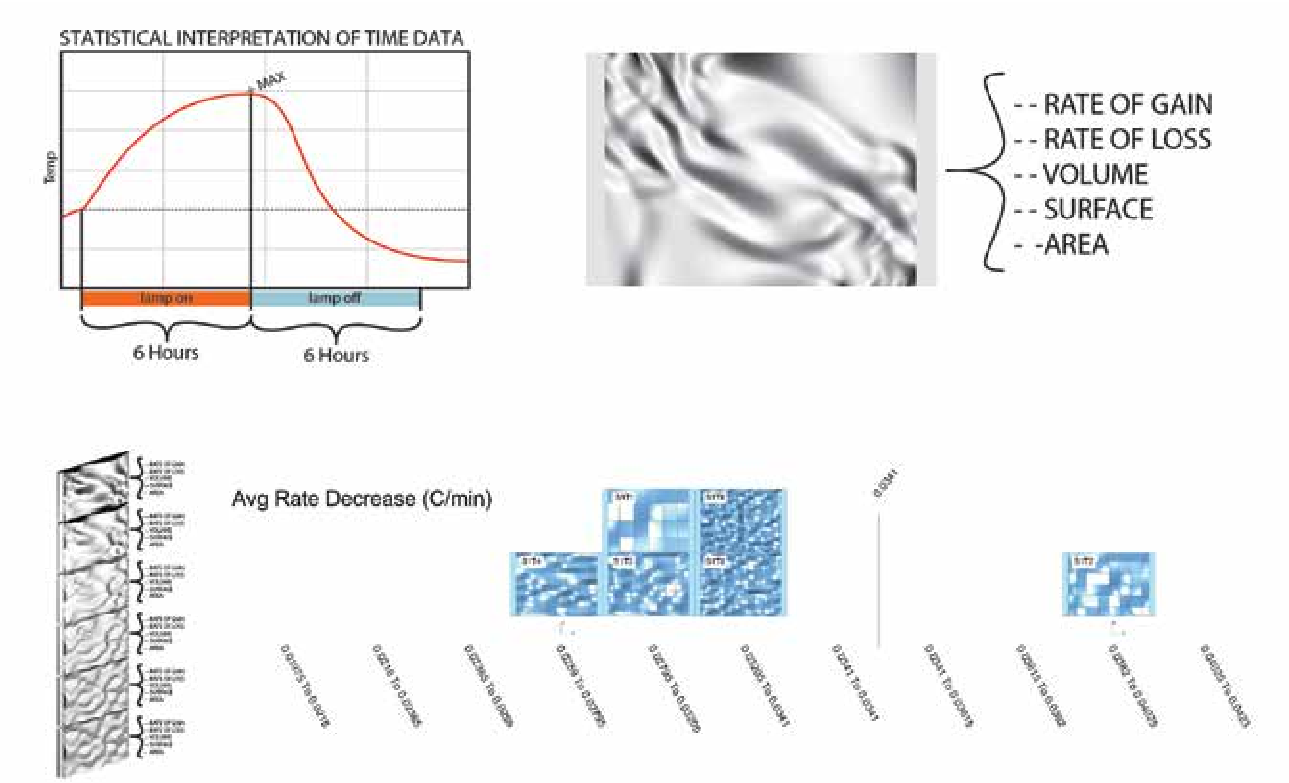
ods and numeric descriptive statistics. The conventional histogram, for example, is typically intended to represent the total frequencies of occurrence and provide "anonymous" interpretation about the totals in a form of abstracted trend of performance. Our method automates the histogram production by utilizing the link between 3d tile geometry and spatialized data set about tile family in relationship to surface area increase, embedding more complex information into the representation. The matrix produced identifies specific performances and their corresponding multi-layered information sets (i.e., average rate increase, thermal gain, etc.), explicitly coupling metrics to the tile pattern inside of the histogram. This histogram then serves directly as a data-based substrate for the next phase of querying logic.

DEFINING QUERYING SYSTEM FOR DESIRED THERMAL ATTRIBUTES

The following phase focuses on making the data set operational within a design process, identifying and querying geometries based on multiple desired performative characteristics. As our study is focused on the thermal properties of complex geometry for specific sample morphologies, we have a population of tiles about which we know specific metrics (fig. 8).

We are able to compare all tiles against performance of increasing temperature and decreasing temperature, as displayed in Figure 9. GH script allows us to automatically visualize the thermal range while matching each pattern to a rate of heat gain or loss. To navigate the design process, one needs to engage the overlap between stochastic understanding of the system and generative abilities of the computational workflow. The designer has a choice to select the tile types and then apply them as desired within specific design systems. the design process, one needs to engage the overlap between stochastic understanding of the system and generative abilities of the computational workflow. The designer has a choice to select the tile types and then apply them as desired within specific design systems.

As our initial set was limited to only 36 tiles, this was also a moment when we attempted to expand on the previous work and, based on our findings, generate a more nuanced geometric variation set (fig. 10). We developed a new series of geometries genetically optimized to produce a tighter constrained testing set, still maintaining consistent tile volume while allowing surface area to increase. This is the foundation of a future phase of the project that will potentially enable us to generate a larger rule-based variety of functional forms automated into new performative patterns.



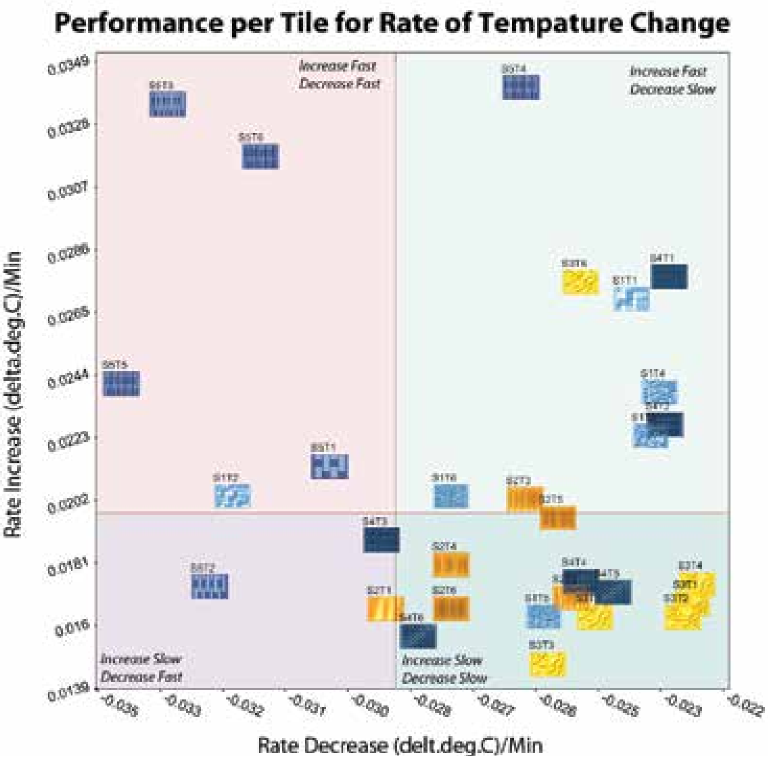
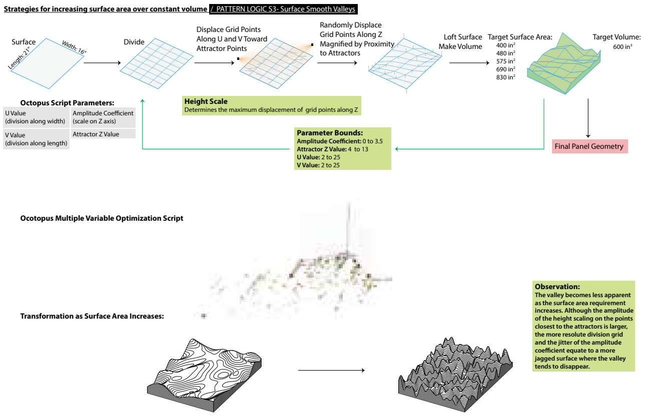
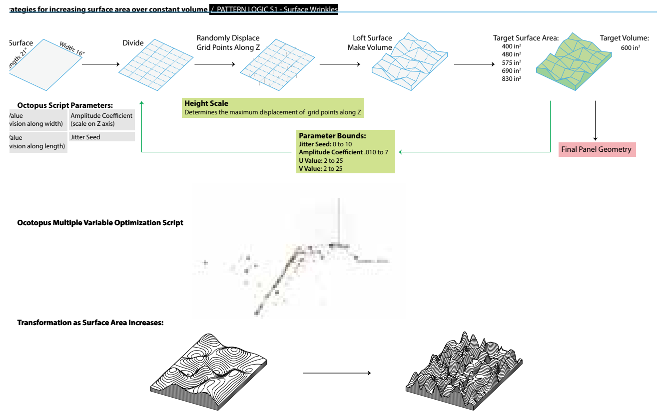


Figure 8: Performance parameters from thermal data are attributed to the virtual time geometries; these can be queried for performance comparison or further generative association. Epiphyte Lab, 2014.

Figure 9: Performance graph per tile for rate of temperature change showing the pattern and performance trending. Epiphyte Lab, 2014.





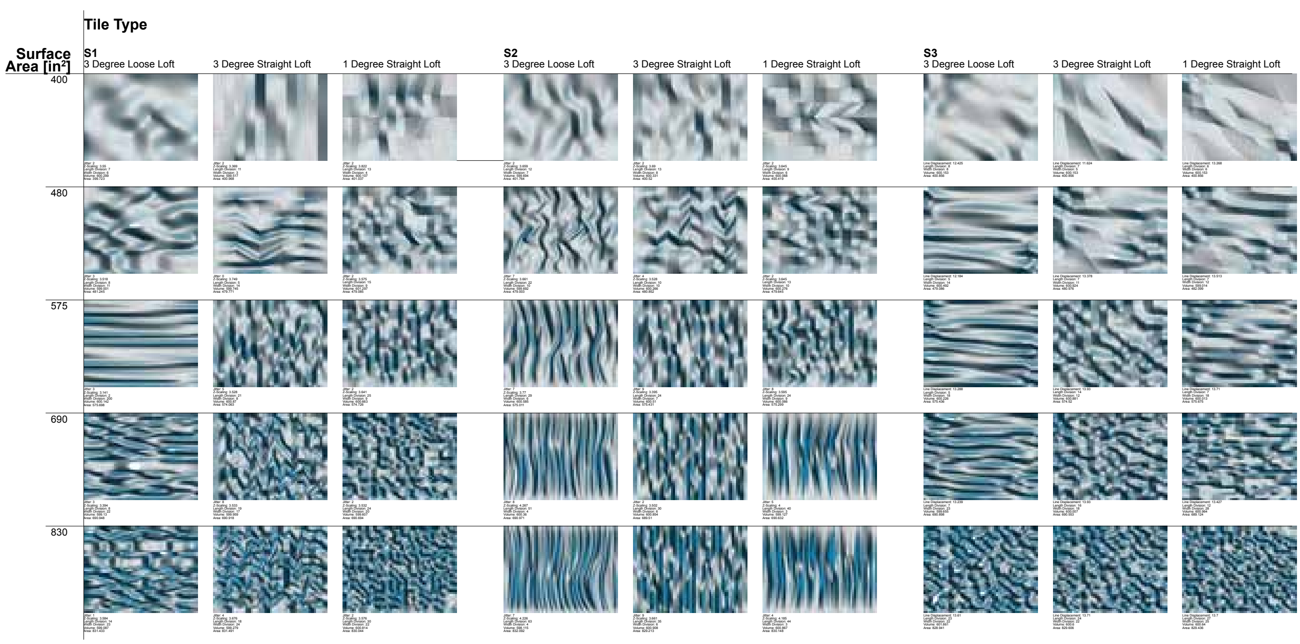


Figure 10: Sample morphologies using Octopus plugin (www.food4rhino.com/project/octopus?ufh) generative script based on genetic optimization of multi-variable constraint of volume to surface area across the family types to produce new generation of thermal morphologies. Epiphyte Lab, 2014.

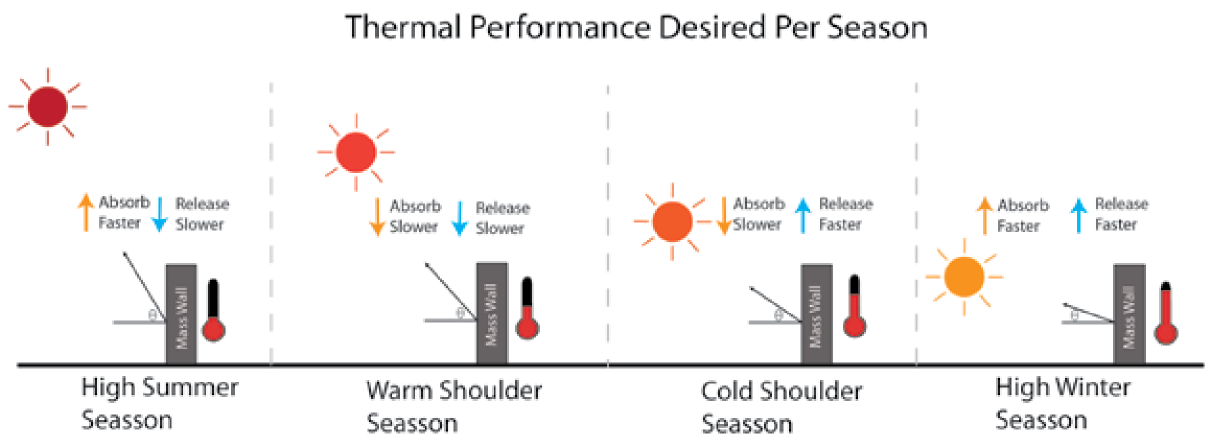


Figure 11: Diagram of Seasonal Solar Exposure of Thermal Mass to Inform Pattern Distribution. Epiphyte Lab, 2014.

AUTOMATED RE-MAPPING OF THERMAL VALUES TO PATTERN MATCHING FOR SPECIFIC CLIMATIC PERFORMANCE

Of course, developing a detailed understanding of thermal performance for specific concrete tiles is not much use if we are unable to operationalize the information. The final stage of our study is the incorporation of the tile geometries into an architectural thermal mass system based on the need to relate thermal attributes to a specific time delay in temperature re-radiation.

In principal, the mass wall's geometry can help to decrease energy usage by both capturing solar energy and redistributing it over time, serving as a thermal buffer. Such systems passively prevent rapid swings in ambient temperature, thus significantly reducing the building's heating loads and needs for additional mechanical systems.

The desired operability and performance of a mass wall varies from one climate to another, as well as throughout the seasons. Tuning such performance thus depends on a number of variables based on site climate and project context (fig. 11). This process of nuanced morphological manipulation is less about the optimization routines and more about understanding the general thermodynamic trends that can be enhanced and enriched by the pattern logic for performance, design purposes, and spatial effects.

In this final phase, we generated a script utilizing basic daylighting simulation in GH and Ladybug[7] plugins, coupling the incident radiation values for a specific time period with the performance rate of geometries (particular speed of thermal absorbency and release). The desired attributes are determined by both the incident radiation simulation and the climate of the location for which radiation was simulated.

The script relies on climactic information extracted from the weather file (.epw), contextualizing and orienting the tested geometry. The script includes a built-in variability that allows for defining the reception surface of thermal mass and its surrounding geometry through basic modeling procedures, while respecting cardinal ordination and the system's scale. The simulation time-span and season can be selected to target a desired performative outcome. By turning on and running the simulation, the receiving surface is matched to the tiling logic by a basic UV subdivision and receives radiation values. The analysis returns the numerical values producing the color mapping of the mesh. It is important that the simulation values have the same ratio as the tile dimensions: As a tile's performance is linked to the specific ratio between its mass and surface area, it is critical that the pattern scale is preserved and UV subdivisions are matched. The simulation returns trimmed surfaces, as well as their basic geometric parameters: center points, normal vectors, and planes. Color mapping is then paired with geometric pattern attributes, which serves as a vehicle for automatic redistribution of the tiles and generation of the overall design. The radiation values for each trimmed surface serve as a substrate to determine the panel location. Within the code, the radiation range serves as a bridge between location and ordination of a particular geometry.

For example: For a wall in Pittsburgh (in figs. 12a and 12b) that seeks to gain heat quickly and release heat slowly during the summer, we can query tiles with the greatest (x, y) values in the scatter plot and then map them across the wall based on radiation levels and tile attributes. Tiles with a fast rate of heat gain and slow release behavior are being mapped as red pixels with highest radiation values, illustrating the

Figure 12a: Diagram showing synthetic application of automated redistribution of pattern logic associated with varied climate. Epiphyte Lab, 2014.

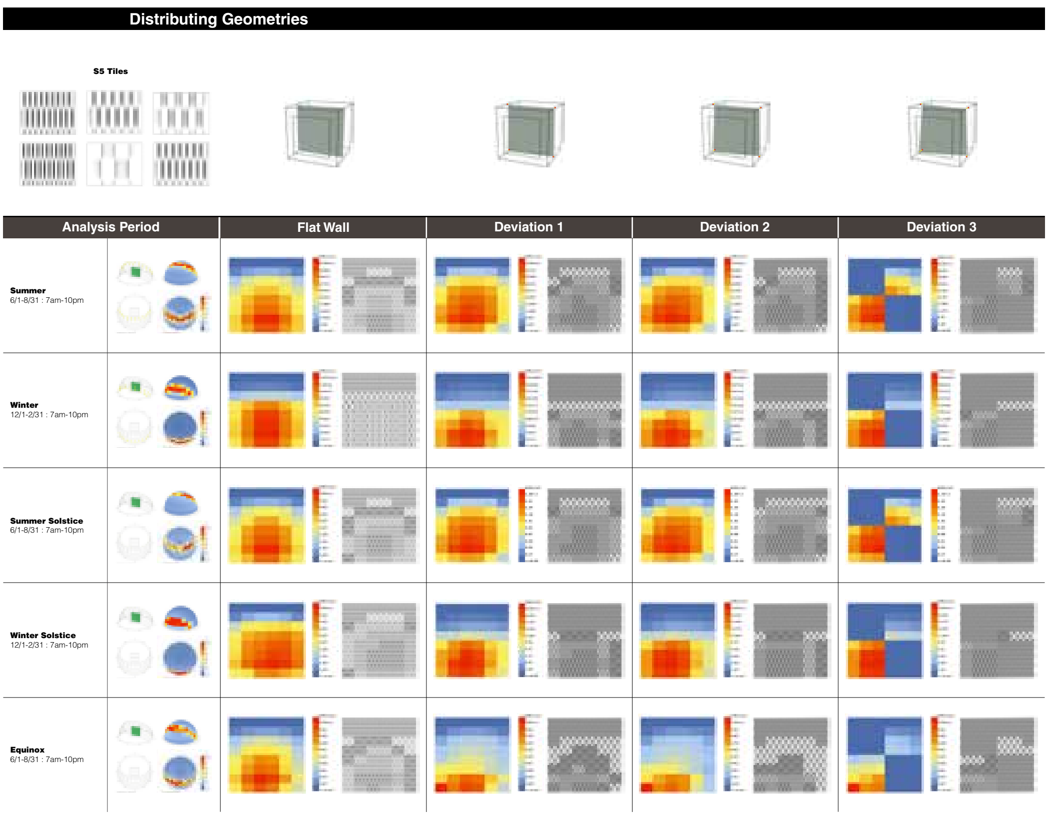


Figure 12b: Diagram showing synthetic application of automated redistribution of pattern logic associated with same climate, but varied 3d geometry of the 'reception' surface. Epiphyte Lab, 2014.

most effective location for these geometries within the mass wall system.

In this script, we can control the location, the way the mass wall is integrated into the building,[8] the shape of the wall, and the desired impact of the wall. Changes in any of these variables produce specific results whose aesthetic is imprinted with the logics of performance, and the wall's context within a particular place.

CONCLUSION

The use of computation empowers the designer by allowing for greater versatility and agility throughout the design process. This workflow translates data processing and archiving across numeric and visual boundaries, allowing for more intuitive design decisions while maintaining the integrity of the pure data. As such, data becomes integral to the navigation of formal decisions, allowing the designer to respond to building attributes and a dynamic environmental context.

ENDNOTES

1. Kevin Pratt et al., "Automated translation of architectural models for energy simulation," SimAUD '12, *Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design,* Article no. 6.

2. David Rutten, Grasshopper, version 0.9.0072 (McNeel, 2014).

3. Dana Cupkova and Nicolas Azel, "Mass Regimes: Geometrically actuated thermal flows," ACADIA '14, *Proceedings of the Conference on Association for Computer Aided Design in Architecture* (Los Angeles, California, 2014).

4. A Trombe wall is a passive solar building design explored and patented by Edward S. Morse in 1881 and further developed by French engineer Felix Trombe in the 1960s.

5. Davit Rutten, Galapagos Evolutionary Solver, www.grasshopper3d.com/group/galapagos.

6. JavaScript Object Notation, http://json.org/

7. Mostapha Sadeghipour Roudsari, LadyBug for Grasshopper, www.grasshopper3d.com/group/ladybug

8. In these tests, the surface is simulated behind glass as per Trombe wall setup.

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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

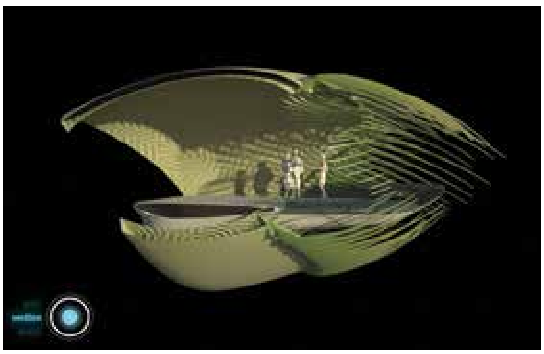
Apertures – view of smaller apertures

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-

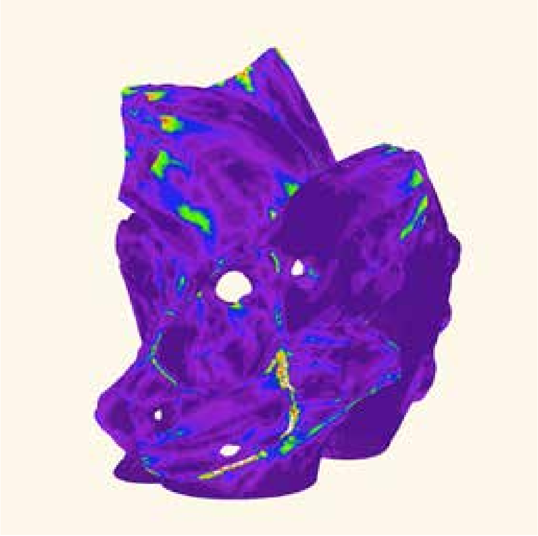
Daniel Libeskind's Jewish Museum in Berlin, Germany

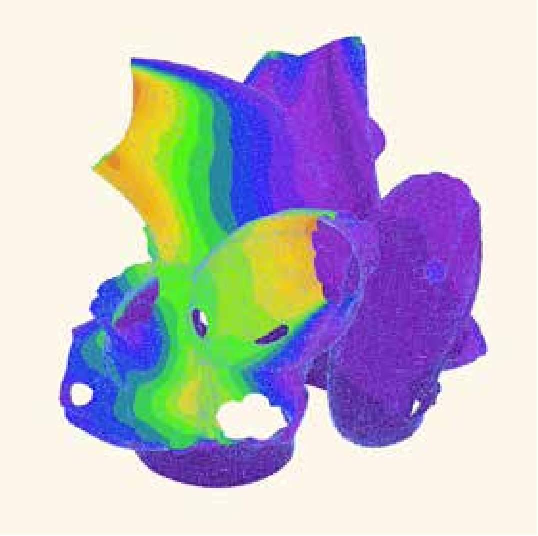
Apertures – interior view

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

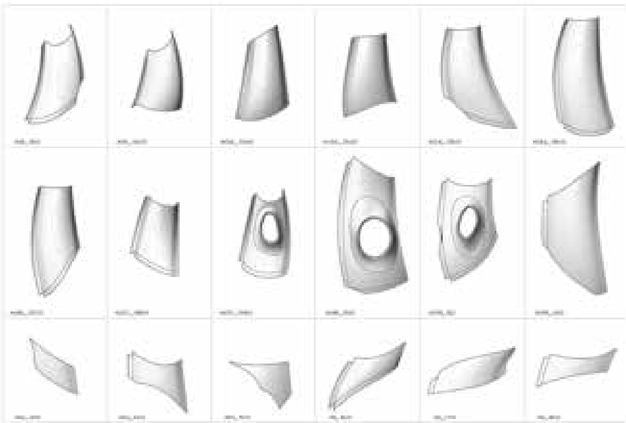
In the typical architectural project, we have adopted construction industry standards of constructing buildings in layers where work has been traditionally divided up by trade. Each of these industries is highly specialized, and coordination between trades has become a highly complex task that results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



CNC mill file layout per component

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.

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.

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.

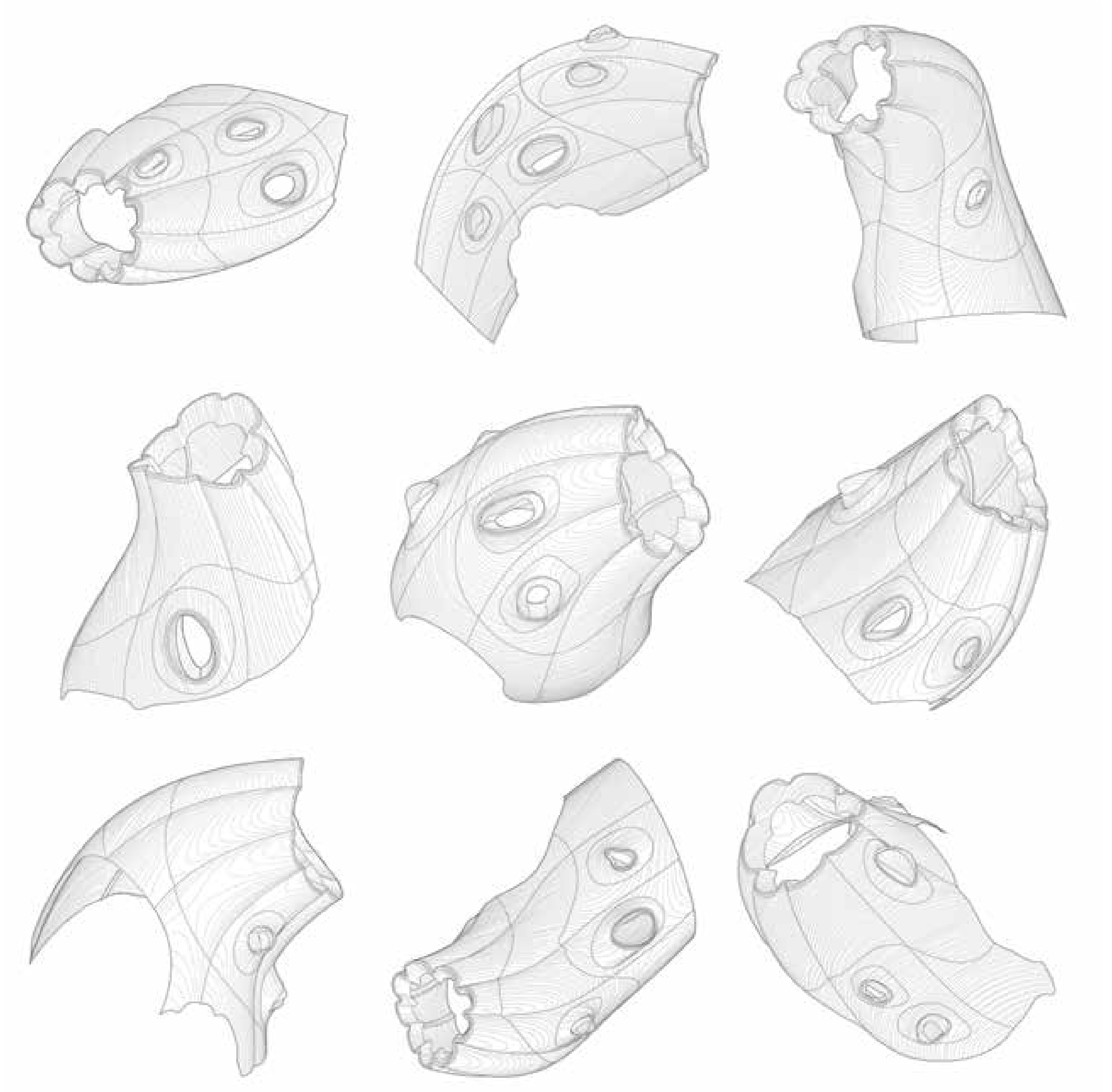
CNC milling

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



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

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.

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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